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RESEARCH MEMORANDUM

ALTITUDE PERFORMANCE OF AN-F-58 FUELS IN BRITISH ROLLS-ROYCE NENE SINGLE COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

July 8, 1949

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ALTITUDE PERFORMANCE OF AN-F-58 FUELS IN BRITISH ROLLS-ROYCE NENE SINGLE COMBUSTOR

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SUMMARY

An investigation was conducted with a single combustor from a British Rolls-Royce Nene turbojet engine to determine the altitude performance characteristics of AN-F-58 fuels. Three fuel blends conforming to AN-F-58 specifications were prepared in order to determine the influence of fuel boiling temperatures and aromatic content on combustion efficiencies and altitude operational limits. The performance of the three AN-F-58 fuels was compared in the range of altitudes from sea level to 65,000 feet, engine speeds from 40- to 100-percent normal rated, and flight Mach numbers of 0.0 and 0.6. Similar information was obtained for AN-F-32 fuel at a flight Mach number of 0.0.

The altitude operational limits of the three AN-F-58 fuels were the same at rated speed and flight Mach numbers of 0.0 and 0.6. The high-aromatic AN-F-58 fuel gave altitude limits below those of the base-stock and high-end point AN-F-58 fuels at lower engine speeds, being about 10,000 feet (flight Mach number, 0.0) and 5000 feet (flight Mach number, 0.6) lower at 70-percent normal rated engine speed. The altitude operational limits of AN-F-32 fuel were about the same as those for the base-stock and high-end-point AN-F-58 fuels at a flight Mach number of 0.0.

The combustion efficiencies with the four fuels ranged from 54.5 to 100 percent with the higher efficiencies occurring at low altitudes and high engine speeds. Although the scatter of data was large, some indication existed that combustion efficiencies with the high-aromatic fuel decreased more rapidly than the other fuels as the engine speed was decreased and as the altitude was increased.

Carbon deposition during operation with the three AN-F-58 fuels was slight.

INTRODUCTION

The potential availability of AN-F-32 fuel for jet-propulsion engines is relatively small because of limitations in boiling range and composition. In order to increase the potential supply of fuel for jet-propulsion engines, fuel AN-F-58, which has wider specification limits, has been proposed. A comprehensive program was undertaken at the NACA Lewis laboratory to determine the performance characteristics of fuels conforming to AN-F-58 specification in current turbojet engines and single combustors from these engines. In the single-combustor investigations, special attention was given to the influence of physical properties of AN-F-58 fuel on combustor performance in order to determine whether the limitations on physical properties in the specification required revision.

The effects of boiling-temperature range and aromatic hydrocarbon concentration within AN-F-58 specification on altitude performance in a single combustor from a British Rolls-Royce Nene turbojet engine are presented. Combustion efficiencies and altitude operational limits were determined in the range of altitudes from sea level to 65,000 feet, engine speeds from 40 to 100 percent normal rated, and flight Mach numbers of 0.0 and 0.6 for three AN-F-58 fuels.

Comparison of the performances of AN-F-58 fuels and AN-F-32 fuel was made at a flight Mach number of 0.0. Comparison of the carbon deposition of the three AN-F-58 fuels at one altitude condition was also made.

FUELS

Specifications and analyses for the fuels used in this investigation are presented in table I.

Three fuels conforming to AN-F-58 specification were used. The first of these (NACA fuel 48-249) was a uniform mixture from several tank-car lots of AN-F-58 fuel as received from the supplier. For purposes of this investigation, this fuel with a boiling range from 110° to 560° F and an aromatic hydrocarbon content of 19 percent was considered a base stock. A second AN-F-58 fuel (NACA fuel 48-258) was prepared by blending 92 percent of the base stock with 8 percent of a number 3 fuel oil. The resulting blend had a boiling range from 110° to 590° F and an aromatic hydrocarbon content of 19 percent. This blend is hereinafter identified as the high-end-point fuel. Comparisons of these fuels (NACA fuels 48-249 and 48-258) were intended to indicate the effect of fuel boiling range on turbojet-engine performance.

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A third AN-F-58 fuel (NACA fuel 48-279) was prepared by blending 79 percent of the base stock with 13 percent of redistilled hydroformate bottoms and 8 percent of number 3 fuel oil. The resulting fuel blend, which boiled between 110° and 590° F and contained 29 percent of aromatics, approaches the AN-F-58 specification limits of final boiling temperature and aromatic content. This blend is hereinafter identified as the high-aromatic fuel. Comparisons of this fuel (NACA fuel 48-279) with NACA fuel 48-258 were intended to indicate the influence of aromatic content on turbojet-engine performance. The addition of the hydroformate bottoms, however, increased the boiling temperatures throughout most of the distillation range (cf. NACA fuels 48-258 and 48-279, table I) and therefore any influence this fuel may have on turbojet-engine performance may not be due solely to aromatic content.

Inasmuch as the silica-gel determination for aromatic content (table I) is considered more reliable than A.S.T.M. determinations for AN-F-58 fuels, all aromatic concentrations referred to were made by the silica-gel method.

APPARATUS AND INSTRUMENTATION

A photograph of the British Rolls-Royce Nene combustor installation is shown in figure 1. All combustor parts between the connecting air pipe and the discharge nozzle are production parts obtained from the manufacturer.

The complete experimental setup is diagrammed in figure 2. Combustion air flow was measured by a thin-plate orifice and was controlled by two butterfly valves downstream of the orifice. The combustor-inlet pressure was adjusted by positioning a butterfly valve downstream of the combustor and the inlet temperature was controlled by a gasoline-fired preheater. Exhaust gases were cooled by a water spray downstream of the combustor and passed into the laboratory exhaust facilities.

The combustor-inlet total pressure and temperature were measured in the 12-inch pipe at plane A (fig. 2) by use of two of the three-point pressure rakes and two of the two-junction iron-constantan thermocouple rakes illustrated in figure 3. The temperature of the exhaust gases was measured by six, five-junction chromel-alumel thermocouple rakes (fig. 3), with thermocouple junctions located at centers of equal areas in the outlet of the combustor at plane B of figure 2. The combustor-outlet pressure rakes and combustor static connections evident in figure 1 were not used in this investigation.

PROCEDURE

Combustor-performance determinations were conducted at simulated altitudes ranging from sea level to 65,000 feet (or at as high a simulated altitude as the laboratory services permitted), at simulated engine rotor speeds from 40 to 100 percent of normal rated speed, and at simulated flight Mach numbers of 0.0 and 0.6.

The combustor-inlet-air conditions and the required combustor-outlet temperature for each altitude and engine speed taken from early engine performance data obtained from the NACA Lewis laboratory are shown by the solid curves in figure 4. Further analysis of the experimental data and experimental investigations with the engine in an investigation independent of the one reported herein revealed errors in these engine performance data. The correct data are shown by the dashed curves in figure 4. The errors were not discovered until this investigation was complete and therefore the data from the solid curves were used. Although the early data used are not precisely correct for the Nene engine, their use still permits a valid basis for comparing the performance of the several fuels studied. The values at various engine speeds and altitudes simulated in the single-combustor investigations were derived from the corrected data by using the temperature and pressure ratios for standard atmospheric conditions. The conditions for a flight Mach number of 0.6 were calculated by using the equations for the ideal pressure and temperature changes required to accelerate air at rest to any given Mach number, as shown in reference 1.

In order to determine the altitude operating limits and the combustion efficiencies at various simulated flight conditions, air flow, inlet pressure, and inlet temperature were adjusted to the required values derived from figure 4. The fuel flow was adjusted to obtain the combustor-outlet temperature required at the simulated flight conditions and data were recorded. The combustion efficiency used herein is defined as the ratio of the actual enthalpy rise through the combustor to the heating value of the fuel supplied.

Carbon-deposition determinations were preceded by a removal of all carbon from the combustor. The combustor was then assembled in the setup and conditions of air flow, inlet pressure, and inlet and outlet temperature were adjusted to simulate 90-percent rated engine speed at an altitude of 35,000 feet. After operating for 6 hours, the combustor was again dismantled and inspected for carbon deposits.

DISCUSSION OF RESULTS

Altitude Operation Limits

The altitude operational limits of most combustors (references 2 to 4) are generally caused by the combustors failing to give a sufficiently high value of temperature rise. The British Rolls-Royce Nene combustor is quite different in this respect. The altitude limits with this combustor result from its inability to give sufficiently low values of temperature rise; that is, at certain altitude engine speeds it is possible to run the combustor if the temperature is above the required value but blow-out will occur if the fuel flow is decreased in an attempt to attain the required temperature. The position of the altitude limit at a given engine speed generally is estimated between two experimental points, one at which the required temperature rise is obtained and one at which the required temperature rise is not obtained. Because of limitations in the exhaust facilities, it was impossible to bracket the operational limits at all engine speeds; in some cases the operational limits were therefore estimated from values of temperature rise obtained only below the operational limit. Furthermore, altitude operational limits are difficult to determine experimentally to within less than 2000 feet because of the erratic performance of the combustor at conditions near the altitude limit. For these reasons the altitude limits included herein must necessarily be considered approximations.

The operating conditions at which data were obtained in the investigation of the four fuels are shown in figures 5 and 6 plotted on coordinates of simulated altitude and percent of normal rated speed for flight Mach numbers of 0.0 and 0.6, respectively. The combustion efficiencies, which are discussed in a subsequent section, are indicated next to each operating point. The curves shown in these figures represent the altitude limits of operation with each of the fuels.

The altitude operational limits of the four fuels at a flight Mach number of 0.0 are plotted in figure 7(a). This plot shows that at 100-percent rated engine speed the three AN-F-58 fuels have the same altitude limits, which somewhat exceed that of AN-F-32 fuel. At 70- and 85-percent normal rated engine speeds, the altitude operational limits of the base-stock and the high-end-point AN-F-58 fuels (NACA fuels 48-249 and 48-258) are approximately the same as for AN-F-32 fuel (NACA fuel 48-306). The high-aromatic-content AN-F-58 fuel (NACA fuel 48-279) had altitude limits that fell below the limits for the other fuels at 70-percent normal rated engine speed by approximately 10,000 feet.

The altitude operational limits of the three AN-F-58 fuels at a flight Mach number of 0.6 are plotted in figure 7(b). Again the altitude operational limits of the base-stock and high-end-point AN-F-58 fuels (NACA fuels 48-249 and 48-258) are approximately equivalent throughout the altitude and engine-speed range investigated. The altitude operational limits of the high-aromatic fuel (NACA fuel 48-279) again show a tendency to drop below those of the other fuels at low engine speeds (about 5000 ft at 70-percent normal rated engine speed).

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Combustion Efficiencies

Combustion efficiency with the British Rolls-Royce Nene combustor was quite sensitive to combustor temperature rise, particularly at low engine speeds. Accordingly, difficulty was encountered in reproducing combustion-efficiency data within 4 or 5 percent inasmuch as the combustor-outlet temperature could not be set at the required value (the combustor-outlet temperature is the average of 30 thermocouple indications and had to be estimated during runs) and often differed from this value by as much as 50° F.

The combustion efficiencies listed beside the data points in figures 5 and 6 range from 54.5 to 100 percent. For ease of comparison, these data have been cross-plotted in figure 8 to show the variation of combustion efficiency with altitude for the four fuels at 70- and 100-percent engine speed. Although the scatter of data is large, there is some indication that combustion efficiencies with the high-aromatic fuel (NACA fuel 48-279) decrease more rapidly than efficiencies with the other fuels as the engine speed is decreased and as the altitude is increased. In general, the combustion efficiencies vary with simulated altitude and engine speed in the same manner as with other gas-turbine combustors (for example, references 2 to 4); that is, the efficiencies decrease with increase in altitude or with decrease in engine speed.

Carbon Deposition

Inspection of the combustor liner after operation for 6 hours at the specified conditions with the base-stock AN-F-58 (NACA fuel 48-249) revealed a sooty discoloration around the swirl vanes and near the inlet end of the flame tube and a thin film of carbon baked on the end of the spray nozzle.

Similar deposits occurred with the high-end-point fuel (NACA fuel 48-258). In addition, a ribbon of carbon about 1/16 inch deep and wide was deposited in the shape of scallops running between the upstream air holes.

With the high-aromatic fuel (NACA fuel 48-279) the deposits were very similar to those with the high-end-point fuel (NACA fuel 48-258) except that in addition, three spots of carbon about $1\frac{1}{4}$ inches long by 1/2 inch wide and having a depth of about 1/64 to 1/32 inch were baked on the upstream wall of the flame tube above the air holes.

Thus, although the amount of carbon deposited in the combustor increased as the volatility decreased and as the aromatic hydrocarbon content increased, in no case was the amount of carbon pronounced.

SUMMARY OF RESULTS

The results obtained in an investigation of a single British Rolls-Royce Nene combustor with three AN-F-58 fuels and one AN-F-32 fuel at various simulated altitudes, engine speeds, and at simulated flight Mach numbers of 0.0 and 0.6 are summarized as follows:

1. At both flight Mach numbers, the altitude operational limits of the three AN-F-58 fuels were the same at rated speed. The high-aromatic fuel gave altitude limits below those of the other fuels at lower engine speeds, being about 10,000 feet (Mach number, 0.0) and 5000 feet (Mach number, 0.6) lower at 70-percent normal rated speed. The altitude operational limits of AN-F-32 fuel were about the same as those for the base-stock and high-end-point AN-F-58 fuels at a flight Mach number of 0.0.

2. The combustion efficiencies with the four fuels ranged from 54.5 to 100 percent with the higher efficiencies occurring at low altitudes and high engine speeds. Although the scatter of data was large, there was some indication that combustion efficiencies with the high-aromatic fuel decreased more rapidly than the other fuels as the engine speed was decreased and as the altitude was increased.

3. The quantity of carbon deposited from any of the fuels was slight. The amount of carbon increased with increase in boiling range and with increase in aromatic content of the fuel.

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2. Childs, J. Howard, McCafferty, Richard J., and Surine, Oakley W.: Effect of Combustor-Inlet Conditions on Performance of an Annular Turbojet Combustor. NACA TN 1357, 1947.

3. Childs, J. Howard, and McCafferty, Richard J.: Simulated Altitude Performance of Combustor of Westinghouse 19XB-1 Jet-Propulsion Engine. NACA RM E8J29, 1948.

4. Zettle, Eugene V., and Cook, William P.: Performance Investigation of Can-Type Combustor. I - Instrumentation, Altitude Operational Limits, and Combustion Efficiency. NACA RM E8F17, 1948.

TABLE I - SPECIFICATIONS AND ANALYSES OF FUELS USED

NACA Fuel	Specifications		Analyses			
	AN-F-58	AN-F-32	AN-F-58			AN-F-32
			48-249	48-258	48-279	48-306
A.S.T.M. distillation D 86-46, °F						
Initial boiling point						
Percentage evaporated	------------	----------	110	112	110	336
5	------------	----------	135	137	133	349
10	------------	410(max.)	157	157	164	355
20	------------	----------	192	198	215	360
30	------------	----------	230	248	273	365
40	------------	----------	272	291	327	370
50	------------	----------	314	332	370	375
60	------------	----------	351	373	407	381
70	------------	----------	388	410	437	387
80	------------	----------	427	450	464	394
90	425(min.)	490(max.)	473	500	501	405
Final boiling point	600(min.)	572(max.)	560	590	590	446
Residue, (percent)	1.5(max.)	1.5(max.)	1.0	1.0	1.0	1.0
Loss, (percent)	1.5(max.)	1.5(max.)	1.0	1.0	1.0	1.0
Freezing point, (°F)	-76(max.)	-76(max.)	< -76	< -76	< -76	-------
Aromatics, (percent by volume)						
A.S.T.M. D-875-46T	30(max.)	20(max.)	17	17	26	-------
Silica gel	------------	----------	19	19	29	15
Viscosity, (centistokes at -40° F)	10.0(max.)	10.0(max.)	2.67	2.94	4.26	-------
Bromine number	14.0(max.)	3.0(max.)	13.8	13.3	12.4	-------
Reid vapor pressure (lb/sq in.)	5-7	----------	5.4	5.1	4.8	-------
Hydrogen-carbon ratio	------------	----------	0.163	0.161	0.150	0.154
(Btu/lb)	18,200(min.)	----------	18,640	18,690	18,480	18,530
Specific gravity	------------	----------	0.769	0.775	0.806	0.831
Accelerated gum (mg/100 ml)	20.0(max.)	8.0(max.)	2.9	12.4	------	0
Sulfur, (percent by weight)	0.50(max.)	0.20(max.)	0.03	0.04	0.04	0.02
Flash point, (°F)	-----------	110(min.)	------	------	------	-------
Air-jet residue (mg/100 ml)	10.0(max.)	----------	3	5	8	1

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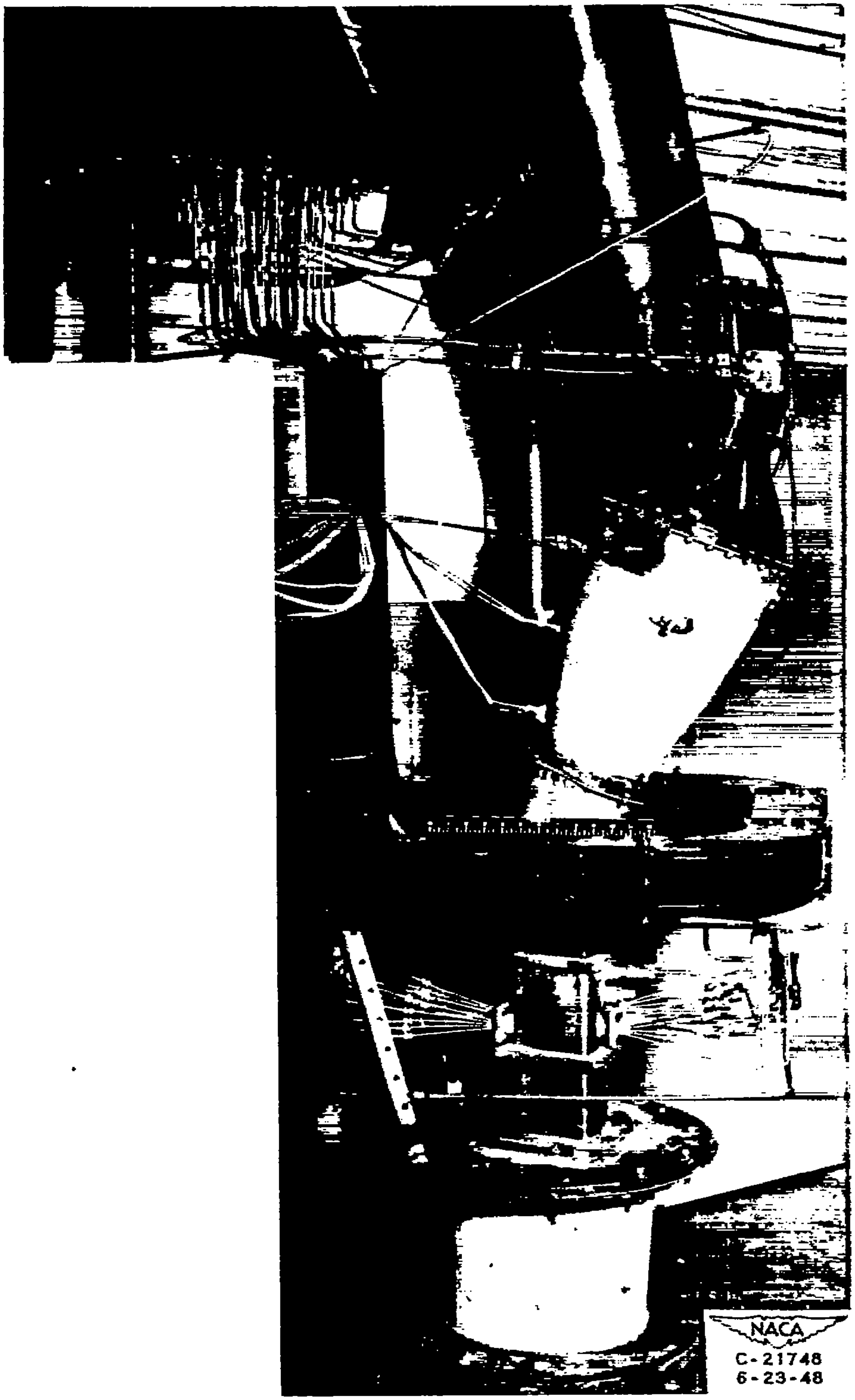


Figure 1. - Single combustor investigated.

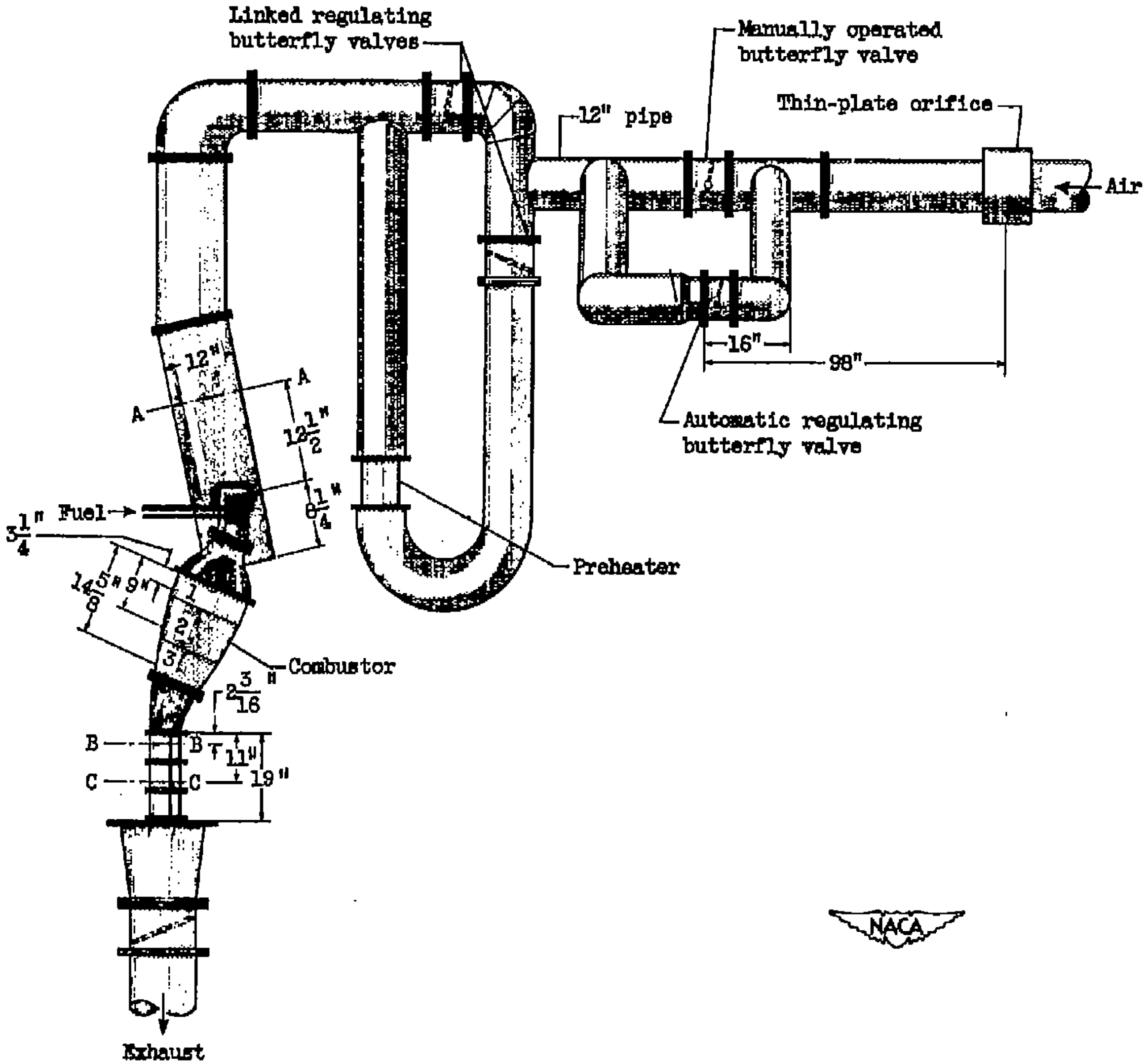


Figure 2. - Diagrammatic sketch of single-combustor setup.

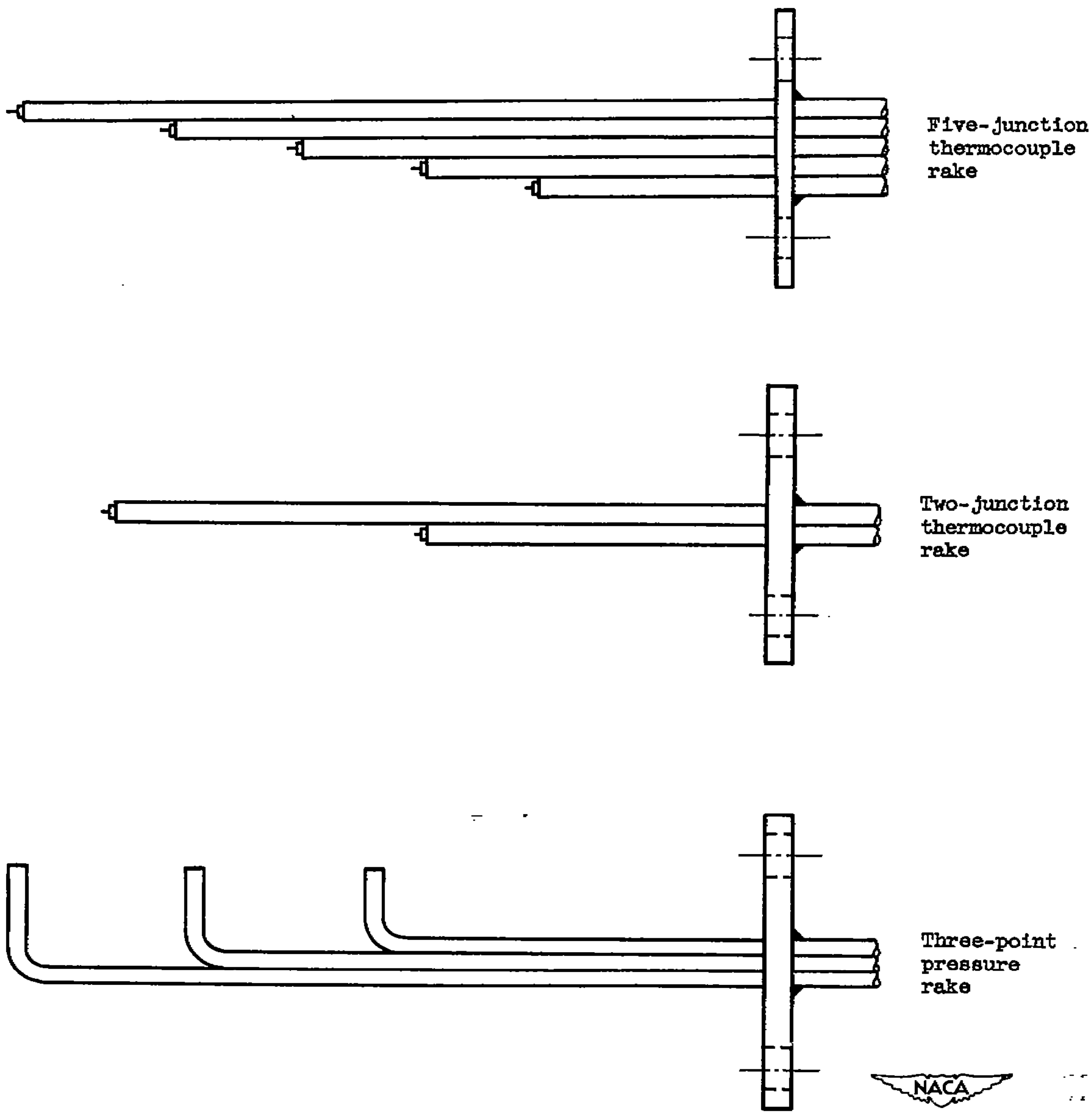


Figure 3. - Temperature- and pressure-measuring devices.

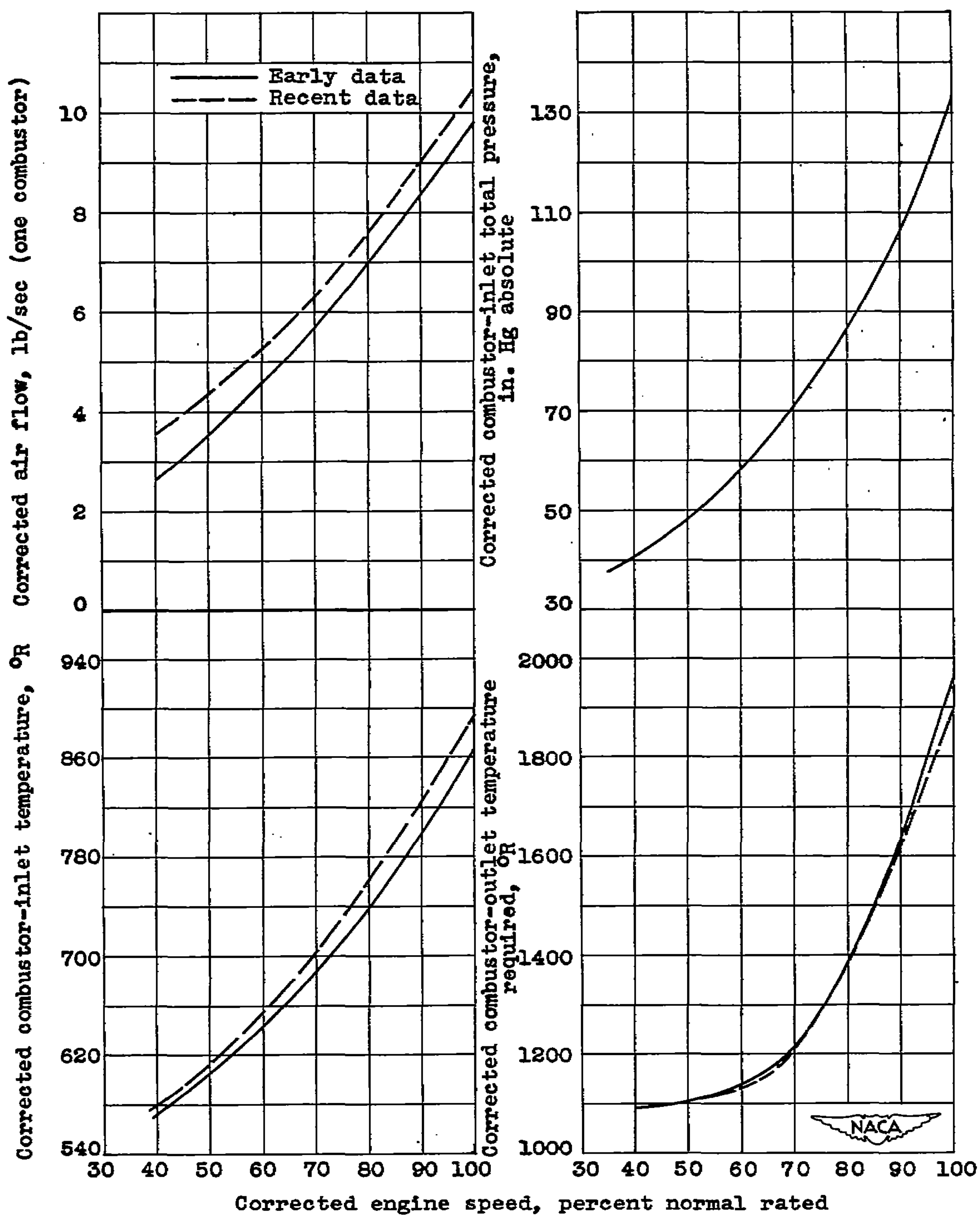
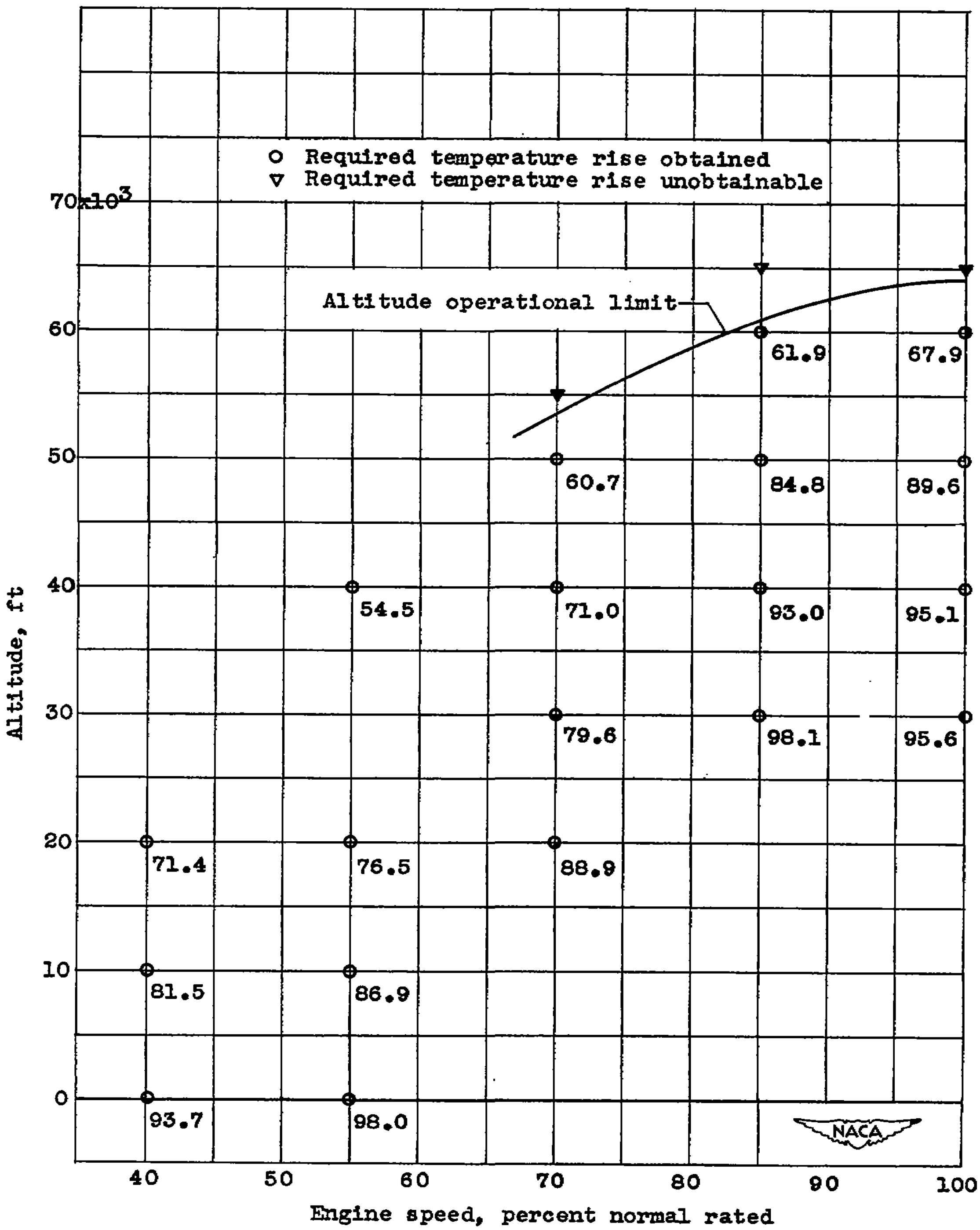
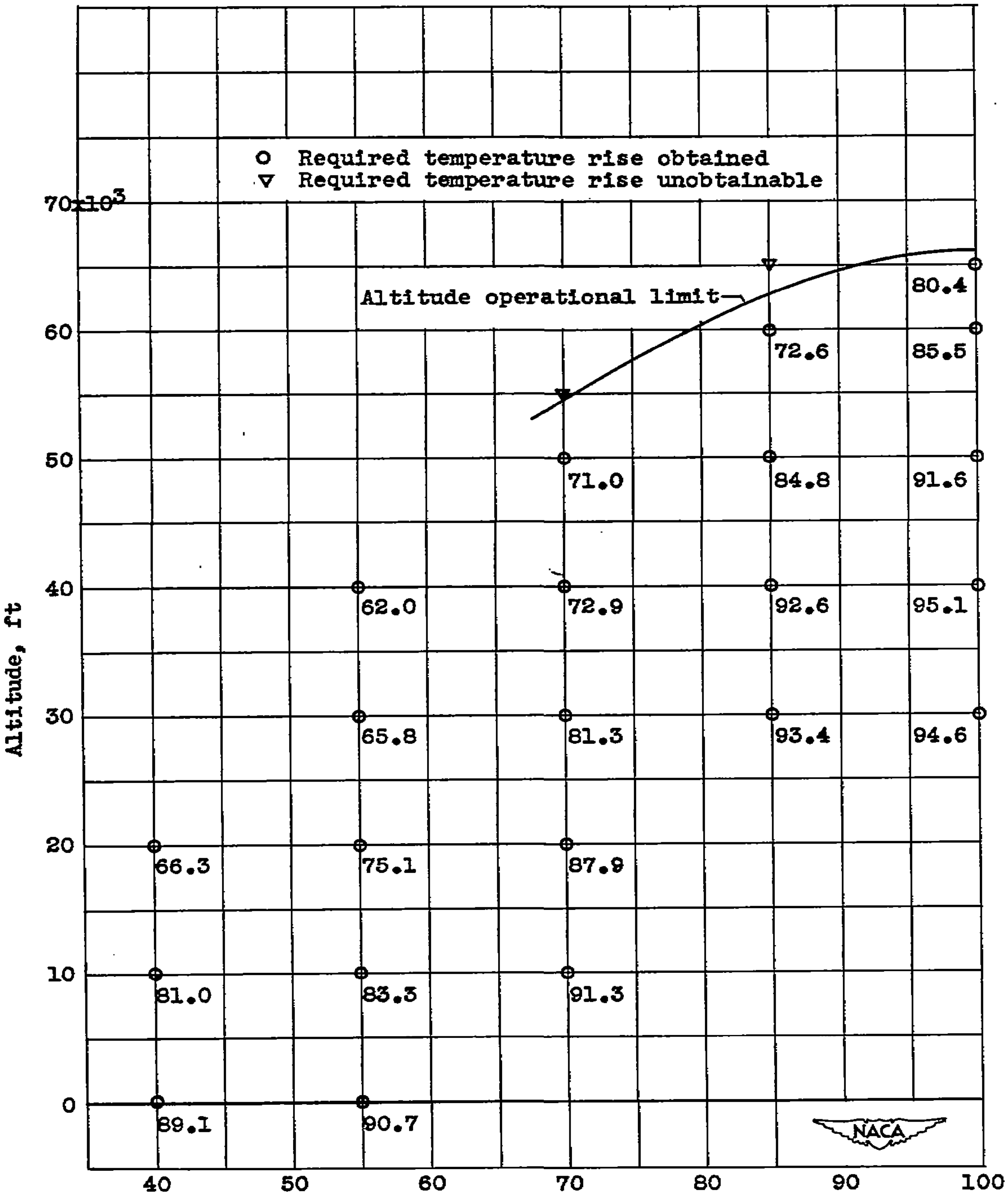


Figure 4. - Single-combustor experimental conditions.



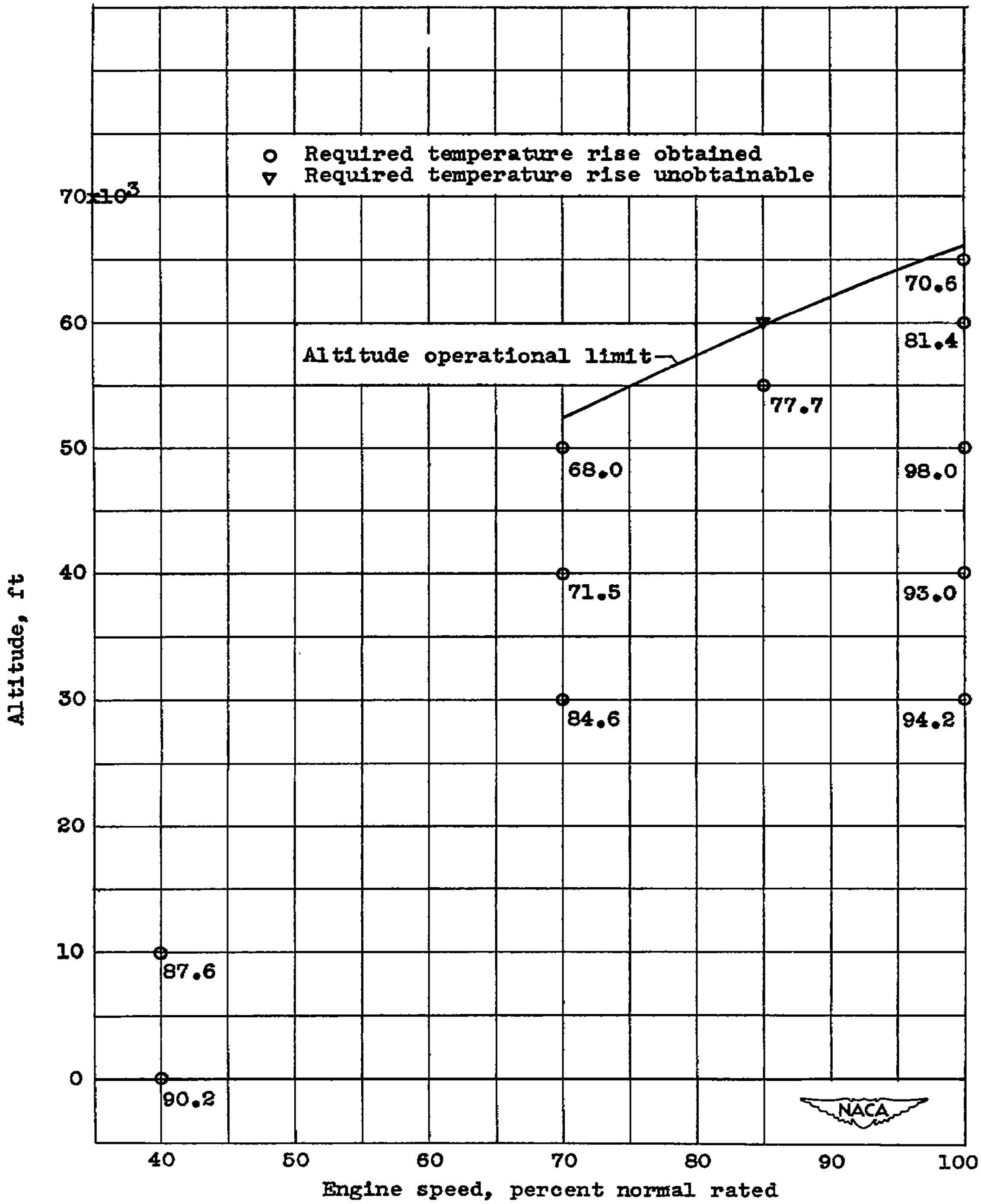
(a) Fuel, AN-F-32 (NACA fuel 48-306).

Figure 5. - Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.0. Values of combustion efficiency in percent are given beside data points.



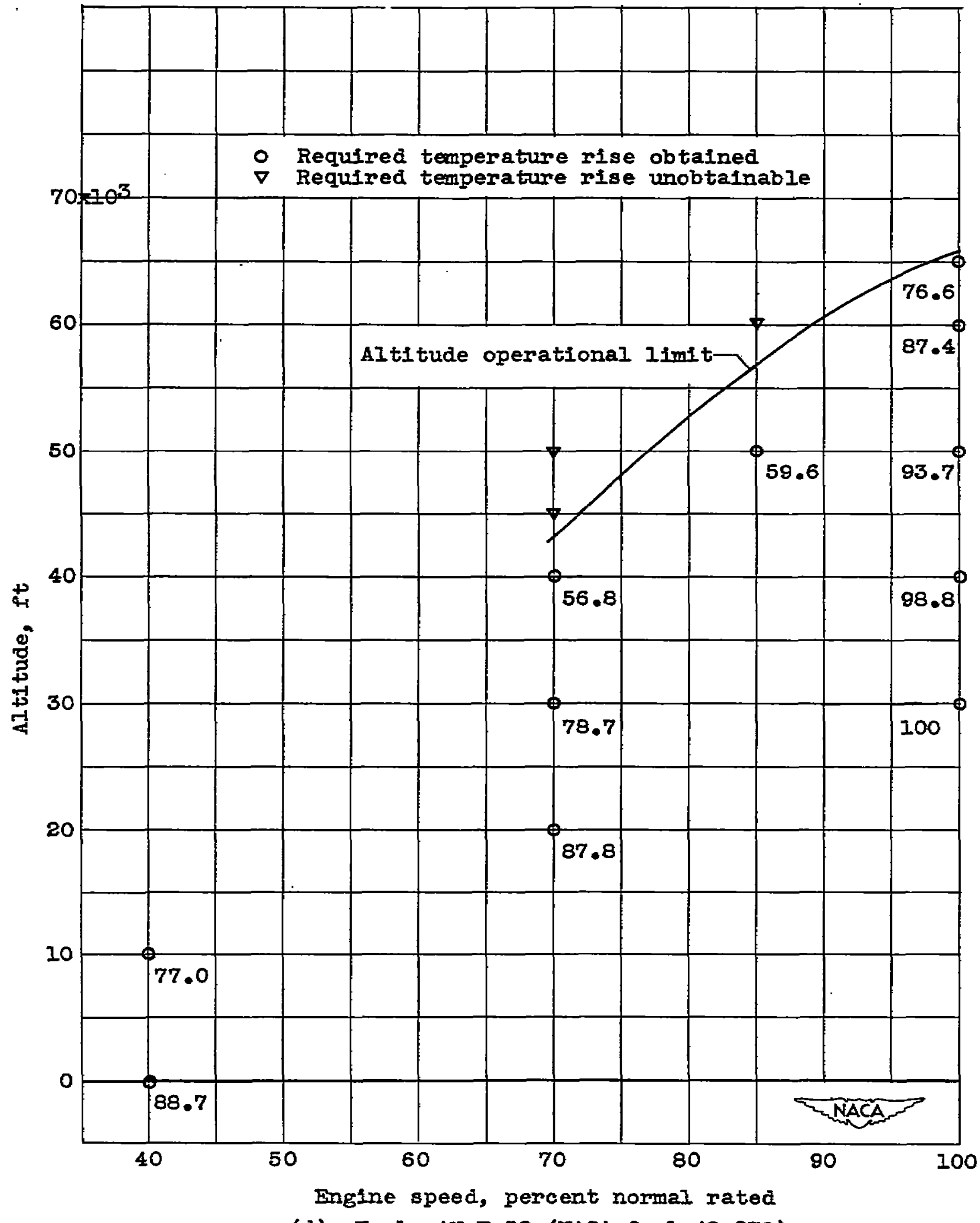
(b) Fuel, AN-F-58 (NACA fuel 48-249).

Figure 5. - Continued. Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.0. Values of combustion efficiency in percent are given beside data points.



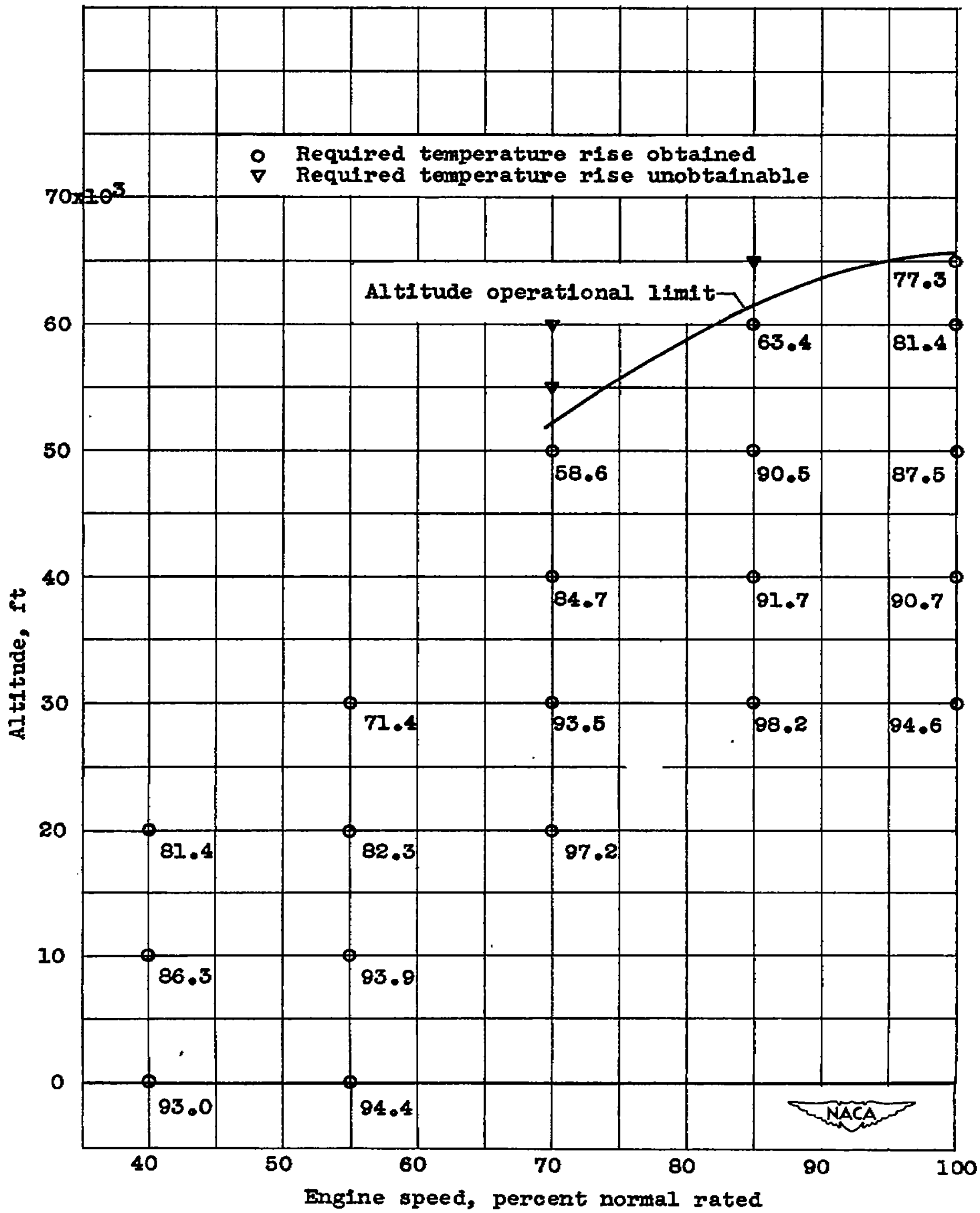
(c) Fuel, AN-F-58 (NACA fuel 48-258).

Figure 5. - Continued. Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.0. Values of combustion efficiency in percent are given beside data points.



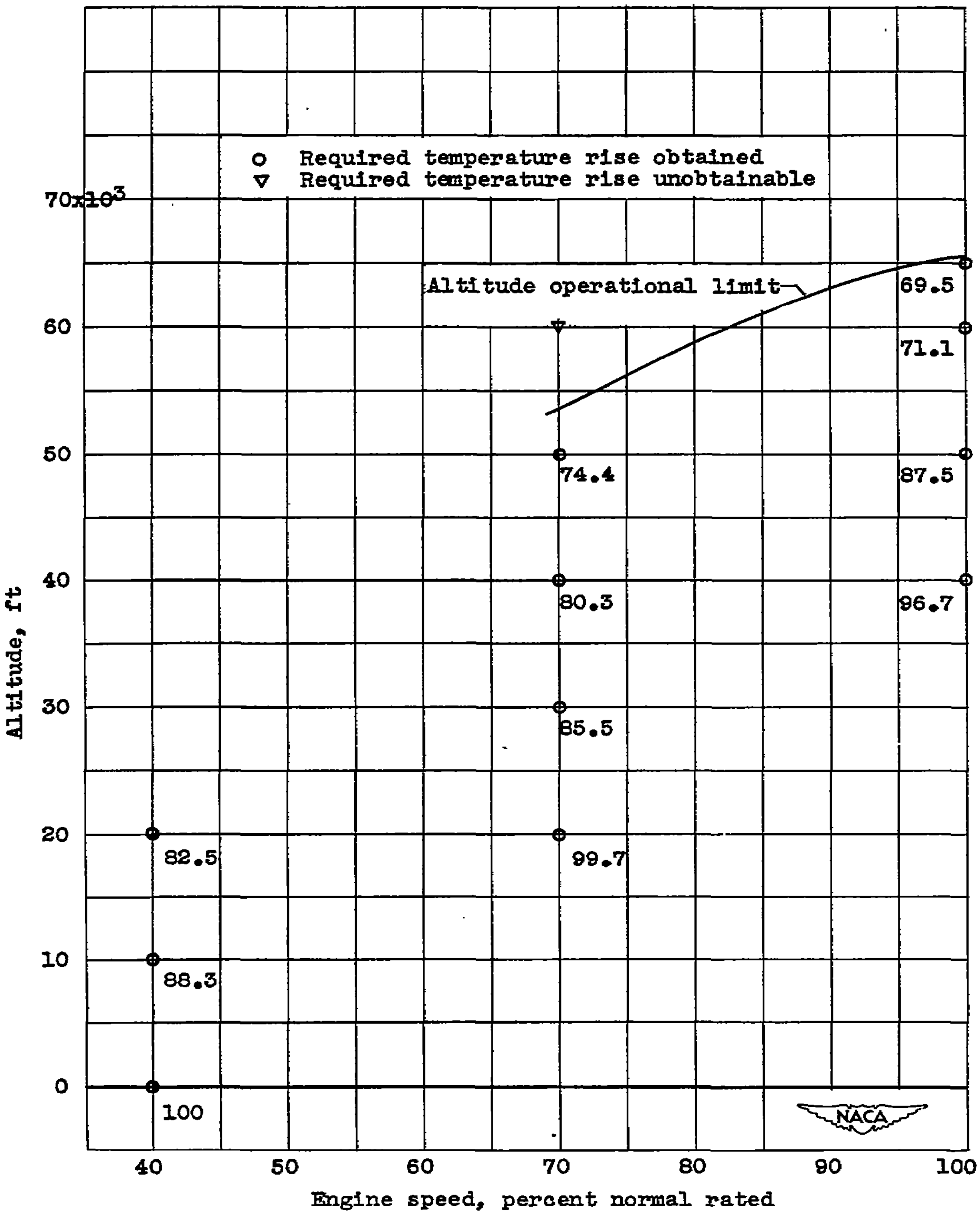
(d) Fuel, AN-F-58 (NACA fuel 48-279).

Figure 5. - Concluded. Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.0. Values of combustion efficiency in percent are given beside data points.



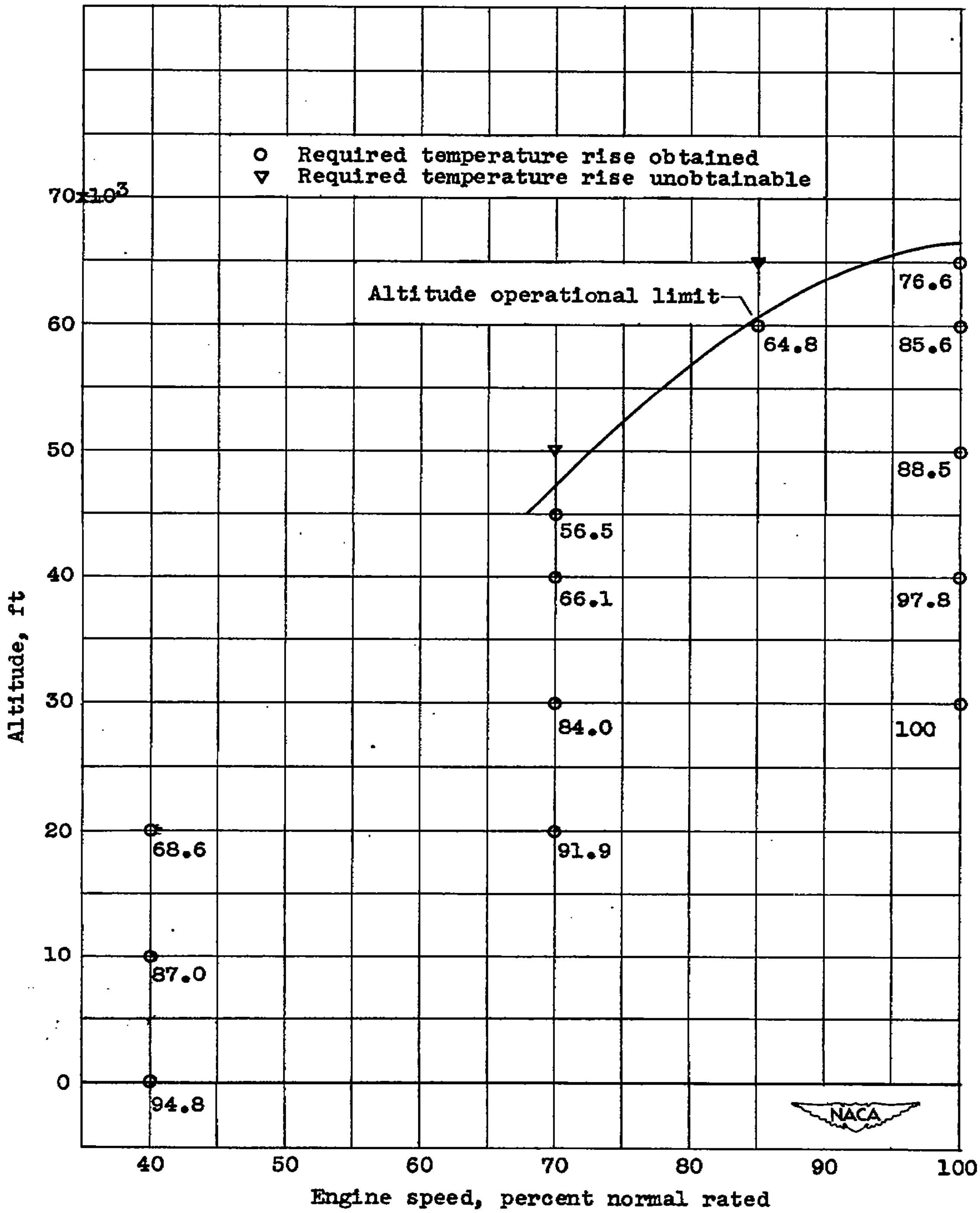
(a) Fuel, AN-F-58 (NACA fuel 48-249).

Figure 6. - Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.6. Values of combustion efficiency in percent are given beside data points.



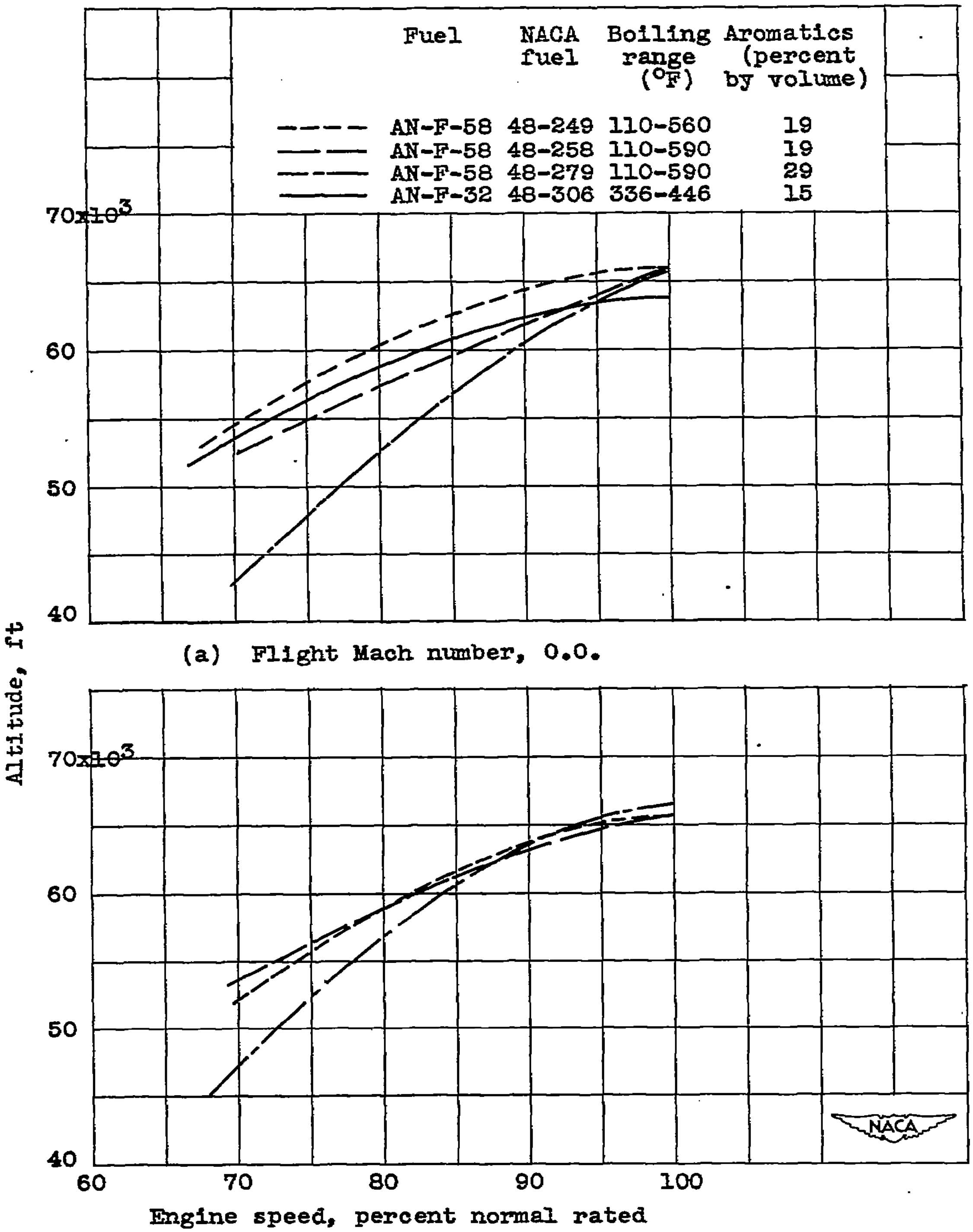
(b) Fuel, AN-F-58 (NACA fuel 48-258).

Figure 6. - Continued. Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.6. Values of combustion efficiency in percent are given beside data points.



(c) Fuel, AN-F-58 (NACA fuel 48-279).

Figure 6. - Concluded. Altitude operational limits and combustion efficiencies of single combustor at flight Mach number of 0.6. Values of combustion efficiency in percent are given beside data points.



(a) Flight Mach number, 0.0.

(b) Flight Mach number, 0.6.

Figure 7. - Comparison of altitude operational limits of various fuels in single combustor.

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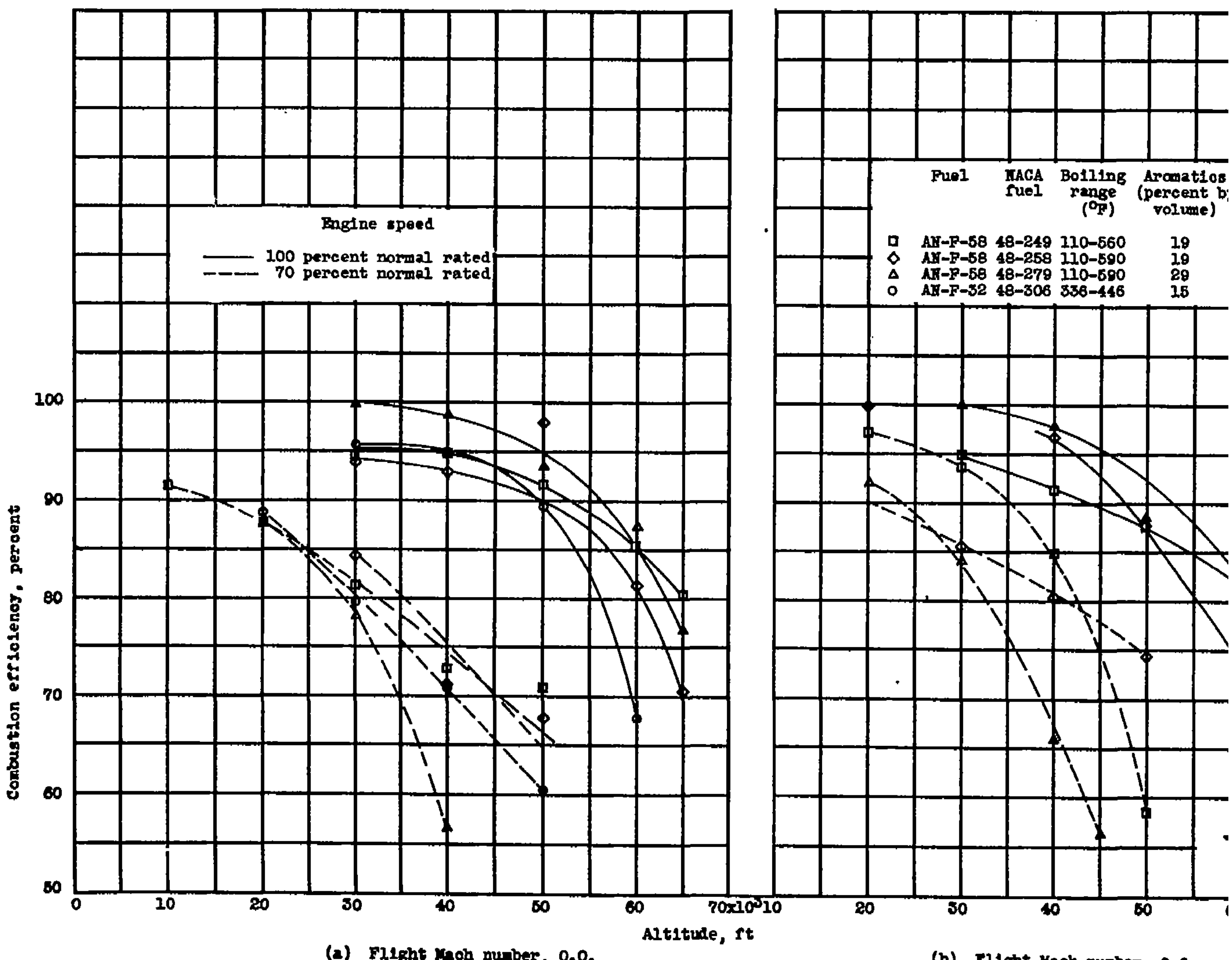

Figure 8. - Effect of altitude on combustion efficiency for AN-F-58 fuels and AN-F-32 fuel in single combustor. (Cross-plotted fro