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RESEARCH MEMORANDUM

COMBUSTION EFFICIENCY AND ALTITUDE OPERATIONAL LIMITS OF THREE LIQUID HYDROCARBON FUELS HAVING HIGH VOLUMETRIC ENERGY CONTENT IN A J33 SINGLE COMBUSTOR

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SUMMARY

The combustion efficiency and the altitude operational limits of three liquid hydrocarbon fuels having high volumetric energy content (decalin, tetralin, and monomethylnaphthalene) were compared with an AN-F-58 fuel in a single tubular combustor from a J33 turbojet engine. The investigation covered a range of simulated engine conditions for altitudes from 20,000 to 60,000 feet; 42- to 107-percent normal rated engine speed; and a flight Mach number of 0.6. The independent effects of combustor-inlet-air temperature, pressure, and mass air flow on the combustion efficiency of the four fuels were determined around a standard combustor-inlet condition.

At the simulated altitude and combustor-inlet-air conditions investigated, the combustion efficiency for the four fuels generally decreased with an increase in volumetric energy content. The highest values of available energy per unit volume of fuel were obtained in this combustor with decalin fuel; although monomethylnaphthalene fuel had the highest volumetric energy content of the fuels tested, its greatly decreased combustion efficiency values resulted in the lowest values of available energy per unit volume.

The altitude operational limits for decalin and tetralin fuels were higher than for AN-F-58 fuel; monomethylnaphthalene fuel gave the lowest altitude operational limit. It was concluded from these and other related investigations that the satisfactory utilization of high-energy-content fuels will require improved fuel-injection techniques and improved combustor design for alleviating the reduced combustion efficiency, the carbon deposition, and the altitude ignition problems.

INTRODUCTION

A program is being conducted at the NACA Lewis laboratory to determine the feasibility of utilizing liquid fuels having higher volumetric energy content than present jet-engine fuels for application to high-speed, volume-limited aircraft. Fuels of this type would permit storage of more energy, in the form of fuel, in a given volume of wing or fuselage. An increase in volumetric energy content for hydrocarbon fuels of interest is usually accompanied by an increase in fuel density; this factor in terms of additional fuel weight would impose a penalty in increased drag because of the additional lift required.

An aerodynamic analysis (unpublished) of the over-all effect of changes in fuel properties on aircraft flight range indicates that, with these high-density hydrocarbon fuels, the energy expended in overcoming the external aircraft drag exceeds the additional energy available because of the higher volumetric heat content of the fuels, thus actually causing a decrease in flight range for the turbojet aircraft. Significant increases in flight range would occur only with low wing-to-fuselage drag ratios (missile-type aircraft) at high supersonic flight speeds.

An increase in the energy content per unit volume for a hydrocarbon fuel is accompanied by a simultaneous increase in fuel boiling temperature (decreased fuel volatility), a decrease in hydrogen-carbon ratio, and an increase in fuel freezing temperature. Some of the possible results of combustor operation with high-energy hydrocarbon fuels are: (1) the reduced volatility of the fuel would decrease altitude boiling and slugging losses, thereby further increasing flight range; (2) the reduced volatility will result in decreased combustion efficiency in current combustion chambers (references 1 and 2); and (3) decreases in the hydrogen-carbon ratio of these fuels may decrease combustion efficiency (reference 1). Combustion-chamber carbon deposition (reference 3) and altitude ignition problems (reference 4) are accentuated in the fuels of low volatility. The higher freezing points limit the type of high-energy hydrocarbon fuel that would be suitable for operation in current turbojet engines.

The investigations reported herein were conducted to evaluate the combustion efficiency and the altitude operational limits in a J33 combustor of three high-energy fuels (decalin, tetralin, and monomethylnaphthalene) having substantially higher volumetric energy content than the current turbojet-engine fuel AN-F-58. Engine conditions were simulated for a range of altitudes from 20,000 to 60,000 feet, engine speeds from 42- to 107-percent normal rated engine rpm, and a flight Mach number of 0.6. In addition, the effects of the combustor-inlet-air pressure, temperature, and mass air flow at two heat-input rates on the combustion efficiency of each fuel were evaluated. The combustion efficiency and the altitude operational limits of the high-energy hydrocarbon fuels are compared with those of the AN-F-58 fuel.

APPARATUS AND PROCEDURE

The installation, controls, and instrumentation of the J33 single combustor are described in detail in reference 5.

Fuels. - The physical and chemical properties of the high-energy fuels decalin, tetralin, and monomethylnaphthalene together with AN-F-58 fuel are presented in table I. The volumetric energy content is defined as the product of the net heat of combustion in Btu per pound and the density in pounds per cubic foot. Decalin, a saturated naphthalene, has a volumetric energy content 14.8 percent greater than that of AN-F-58 fuel; tetralin, a partially saturated naphthalene-type fuel, 17 percent greater; and monomethylnaphthalene, a mixture of α- and β-methylnaphthalenes, 18.8 percent greater. The molecular structures of these fuels are indicated in table I.

Procedure. - The combustion efficiency and the altitude operational limits of the three high-density hydrocarbon fuels and the AN-F-58 reference fuel were determined over a range of simulated engine operating conditions from 42- to 107-percent normal rated speed, altitudes from 20,000 to 60,000 feet, and a flight Mach number of 0.6. Control charts showing required combustor-inlet-air flows, pressures, and temperatures and combustor-outlet-gas temperatures to simulate various altitudes and engine speeds for a J33 engine are presented in reference 5. Reference 5 also presents in detail an operating procedure similar to that used in these tests for obtaining altitude combustion efficiency and altitude operational limits.

In order to determine the effect of combustor-inlet-air conditions, the combustion efficiency was measured over a range of heat-input rates for the four fuels at each of the following inlet-air conditions:

Series	Variable	Combustor-inlet-air conditions		
		Pressure (in. Hg abs.)	Temperature (°F)	Mass air flow[a] (lb/sec/sq ft)
1	Temperature	30.5	90, 160 220, 300	3.74
2	Pressure	15.0, 30.5, 46.0	160	3.74
3	Air flow	30.5	160	2.29, 3.74, 5.2

[a]Mass air-flow rate per unit cross-sectional area of combustor.

Fuel-flow rates at each combustor-inlet-air condition were adjusted to give heat-input rates of approximately 200, 315, and 420 Btu per pound of air. The heat input is the product of fuel-air ratio and the net heat of combustion of the fuel.

The operation of the combustor for this investigation consisted in setting the inlet-air flow, pressure, and temperature at one of the combustor-inlet conditions and, after initiating combustion, adjusting the fuel control to obtain one of the standard heat-input rates. After sufficient time was allowed for the combustor and instrumentation to reach equilibrium, the average combustor-outlet-gas temperature and other pertinent data were recorded.

Combustion efficiency is defined as the ratio of the measured enthalpy rise across the combustor to the heating value of the fuel. This combustion efficiency was determined by the method described in reference 6.

DISCUSSION OF RESULTS

Reproducibility of data. - For the entire test period, daily checks on the performance of the combustor were made at two selected simulated engine conditions; 84.5- and 93.5-percent normal rated speed, 50,000-foot altitude, and a flight Mach number of 0.6. The total deviation in combustion efficiency for the combustor during the course of the investigation is shown in figure 1. Each day represents data taken with AN-F-58 fuel at one or both of the standard engine conditions during a day of operation with one of the three high-energy fuels. The maximum total arithmetic differences in combustion efficiencies for these check points were less than 6 percent for the entire test period. The check points represented an engine operating condition of average severity, and greater day-to-day deviation in combustion efficiency might be encountered near the altitude operational limits where conditions are less favorable and combustor performance is more erratic.

Fuel performance at simulated engine conditions. - The combustion efficiency of the four fuels at simulated engine conditions is plotted in figure 2 against percentage of normal rated engine speed at various altitudes and a flight Mach number of 0.6. Altitude operational limits encountered for the four fuels are also indicated. The combustion efficiency decreases with decreasing engine speed and increasing altitude for all fuels. The minimum permissible engine speed before blow-out was greater at the higher altitudes than at the lower altitudes for all fuels.

For ease of comparison, some of the data from figure 2 is cross-plotted in figure 3 to show the variation of combustion efficiency with altitude for the four fuels at 70- and 90-percent normal rated engine speed. For both simulated engine speeds and any one altitude, the combustion efficiency decreased with an increase in the volumetric energy content of the fuel. This decrease may be caused by the associated increases in the volumetric average boiling temperature and/or the decrease in hydrogen-carbon ratio. Thus AN-F-58 fuel, with the lowest boiling temperature and the highest hydrogen-carbon ratio, operated with the highest combustion efficiencies; and monomethylnaphthalene, with the highest boiling temperature and the lowest hydrogen-carbon ratio, operated with the lowest combustion efficiencies. The spread of the combustion efficiencies for the four fuels at the low engine speed increased from about 15 percent at 20,000 feet to 26 percent at 50,000 feet. At the high engine speed the spread in combustion efficiency increased from about 15 percent at 40,000 feet to about 20 percent at 60,000 feet. Among the high-energy hydrocarbon fuels, decalin operated with the highest combustion efficiency. The combustion efficiency of decalin equaled that of AN-F-58 fuel at 40,000 feet and high engine speeds, and was 10 percent lower at low speeds and 50,000 feet.

The minimum-operational-engine-speed data from figure 2 are cross plotted in figure 4 to compare the altitude operational limits for the four fuels. These points represent the approximate minimum speed at a constant simulated altitude below which combustor operation ceased or the required combustor temperature rise was unobtainable. For the three high-energy fuels the minimum operational engine speed increased with increasing volumetric energy contents. The altitude operating limit for decalin fuel was approximately 7500 feet higher than that for AN-F-58 fuel at an engine speed of 7000. This difference decreased with decreasing minimum engine speed. The monomethylnaphthalene fuel gave the lowest altitude operating limits of the fuels tested.

Although no attempt was made to isolate the independent effects of fuel boiling temperature and molecular structure on altitude operating limits and combustion efficiency, the three high-energy hydrocarbons gave decreasing altitude limits and combustion efficiencies with increasing volumetric average fuel boiling temperature and decreasing hydrogen-carbon ratio. Monomethylnaphthalene fuel was also unsatisfactory from the standpoint of carbon deposition and ignition at the altitudes investigated. 1406

Although carbon deposition was not investigated quantitatively, visual estimates indicated general agreement with the carbon-deposition correlation chart presented in reference 4. This correlation predicts carbon formations for the four fuels in a 4-hour test at 90-percent normal rated speed and 20,000-foot altitude, in a J33 single combustor as follows:

Fuel	Carbon deposited (grams)
AN-F-58	6
Decalin	15
Tetralin	66
Monomethylnaphthalene	160

Altitude starting was not evaluated for the high-energy content fuels used in this investigation, but ignition was noticeably more difficult for these fuels than for AN-F-58 fuel. Initiating combustion with monomethylnaphthalene fuel in particular was critical, and simultaneous high pressure and temperature at the combustor inlet ($1\frac{1}{2}$ atmospheres and 280° F, respectively) were necessary for successful ignition.

Thus, although decalin, tetralin, and monomethylnaphthalene fuels have higher volumetric energy contents than present turbojet fuels, they exhibit lower combustion efficiencies. The net advantage, or disadvantage, of these fuels can be represented by the energy per unit volume released in the combustion process. This energy, the product of the combustion efficiency and the net heat of combustion of the fuel

(Btu/cu ft), is called the available energy per unit volume. The variation of available energy with altitude for the four fuels, at 70- and 90-percent normal rated engine speed, is presented in figure 5. The available energy per unit volume for decalin fuel was 11- to 6-percent higher than for AN-F-58 fuel at altitudes from 40,000 to 60,000 feet and 90-percent normal rated engine speed. In the altitude range from 20,000 to 46,000 feet and 70-percent normal rated engine speed, the available energy was slightly greater for decalin fuel than for AN-F-58 fuel. At altitudes above 46,000 feet decalin fuel gave available energy contents per unit volume less than AN-F-58 fuel. On this same basis tetralin and monomethylnaphthalene fuels were inferior to AN-F-58 at most conditions. In general the differences in available energy among the fuels increased with increasing altitude.

Effect of inlet-air parameters. - The variation of combustion efficiency with combustor-inlet-air temperature, pressure, and mass air flow is presented in figures 6, 7, and 8, respectively, for heat-input rates of 315 and 420 Btu per pound of air (equivalent to fuel-air ratios of approximately 0.017 and 0.022, typical of normal turbojet-combustor operation) with the four fuels.

The effect of combustor-inlet-air temperature on combustion efficiency (fig. 6) represents data taken at an inlet-air pressure of 30.5 inches mercury absolute and a mass air-flow rate of 3.74 pounds per second per square foot. In general, the combustion efficiency of the four fuels increased slightly with increasing combustor-inlet-air temperature at the low heat-input rate, with the less volatile or high-energy fuels showing the most improvement. At the high heat-input rate, the combustion efficiency of the fuels decreased slightly with increasing combustor-inlet-air temperature. The increase in combustion efficiency of AN-F-58 fuel over decalin, the best of the high-energy fuels, varied from about 24 percent at low inlet-air temperatures and the lower heat-input rate to about 6 percent at high inlet-air temperatures and the higher heat-input rate. The variations in combustion efficiency shown in figure 6 represent net effects of increasing inlet-air temperature and inlet-air velocity because these parameters vary simultaneously for conditions of constant inlet-air pressure and mass air flow.

In figure 7, the effect of combustor-inlet-air pressure on combustion efficiency for the four fuels is presented. For these data a constant combustor-inlet-air temperature of 160° F and mass air flow of 3.74 pounds per second per square foot were maintained. In general, increasing the combustor-inlet pressure gave increasing combustion efficiency values for the four fuels at both heat-input rates. The increase in combustion efficiency of AN-F-58 fuel over decalin, the best high-energy fuel, varied from about 13 percent at low inlet-air pressures and the lower heat-input rate to about 4 percent at an inlet-air pressure of 46 inches mercury absolute and the higher heat-input rate. With monomethylnaphthalene, combustion could not be maintained at subatmospheric pressures. The increases in combustion efficiency observed in figure 7 were obtained not only by increasing inlet-air pressure, but also by simultaneously decreasing inlet-air velocity (constant temperature and air-flow condition).

The effect of mass air-flow rate on combustion efficiency at a constant combustor-inlet-air temperature of 160° F and pressure of 30.5 inches mercury absolute for two heat-input rates is shown in figure 8. At a heat-input rate of 420 Btu per pound of air, a moderate increase in combustion efficiency accompanied an increase in mass flow at low-flow conditions. At mass-flow rates greater than 4 pounds per second per square foot, the combustion efficiency was significantly unaffected by further increases in flow rate. Combustion could not be maintained at mass flows greater than about 3.9 pounds per second per square foot with tetralin fuel at the lower heat-input rate. In general, the combustion efficiencies for the fuels investigated increased with decreasing volumetric energy content. The variations in the behavior of the fuels at the lower heat-input rate can be partly explained by the fact that these are curves of constant heat input (or constant fuel-air ratio). As the mass flow is increased at constant pressure and temperature, the air velocity is increased together with the fuel-flow rate. Increases in velocity will normally have an adverse effect on combustion efficiency, whereas increases in fuel-flow rate (particularly at low flows) tend to improve combustion efficiency by improving fuel atomization characteristics.

From figures 6, 7, and 8 it has been seen that the combustion efficiency for the four fuels generally increased with decreasing volumetric energy content and increasing fuel volatility and hydrogen-carbon ratio for the range of inlet-air parameters investigated. The combustion efficiency of the fuels was more sensitive to changes in operating conditions at the lower heat-input rates and lower values of combustor-inlet-air temperature, pressure, or velocity. At all conditions investigated the highest combustion efficiency was obtained with the AN-F-58 fuel and the lowest, with monomethylnaphthalene. At conditions of high inlet-air pressure and temperature, however, the differences among the fuels were small.

SUMMARY OF RESULTS

From an investigation of combustion efficiency and altitude operational limits of three liquid high volumetric energy content fuels, decalin, tetralin, and monomethylnaphthalene, together with an AN-F-58 fuel in a J33 single tubular combustor, the following results were obtained over a wide range of simulated engine altitude and combustor-inlet-air conditions:

1. The combustion efficiencies for the four fuels generally decreased with an increase in volumetric energy content. The increases in volumetric energy content were accompanied by increases in volumetric average boiling point and decreases in hydrogen-carbon ratio.

2. The highest values of available energy per unit volume of fuel were obtained in this combustor with decalin fuel; although monomethylnaphthalene fuel had the highest volumetric energy content of the fuels tested, its corresponding low values of combustion efficiency resulted in the lowest values of available energy per unit volume.

3. The altitude operational limits for decalin and tetralin fuels were higher than those for AN-F-58 fuel; monomethylnaphthalene fuel gave the lowest altitude operational limits.

CONCLUSION

It is concluded from these and related investigations that the satisfactory utilization of high-energy-content fuels will require improved fuel injection techniques and improved combustor design for alleviating the reduced combustion efficiency, the carbon deposition, and the altitude ignition problems.

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REFERENCES

1. Tischler, Adelbert O., and Dittrich, Ralph T.: Fuel Investigation in a Tubular-Type Combustor of a Jet Propulsion Engine at Simulated Altitude Conditions. NACA RM E7F12, 1947.

2. Wear, Jerrold D., and Jonash, Edmund R.: Combustion-Efficiency and Altitude-Limit Investigations of Five Fuels in an Annular Turbojet Combustor. NACA RM E7L30, 1948.

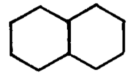
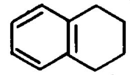
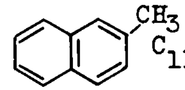
3. Wear, Jerrold D., and Jonash, Edmund R.: Carbon Deposition of 19 Fuels in an Annular Turbojet Combustor. NACA RM E8K22, 1949.

4. Rayle, Warren D., and Douglass, Howard W.: Investigation of Ignition Characteristics of AN-F-32 and Two AN-F-58a Fuels in Single Can-Type Turbojet Combustor. NACA RM E50H16a, 1950.

5. Dittrich, Ralph T., and Jackson, Joseph L.: Altitude Performance of AN-F-58 Fuels in J33-A-21 Single Combustor. NACA RM E8L24, 1949.

6. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Pressure. NACA Rep. 937, 1949.

TABLE I - PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF FUELS

Fuel NACA No.	AN-F-58 48-249	Decalin 49-147	Tetralin 49-146	Monomethylnaphthalene 49-148
Structure or composition	Aromatics, 18.5 Olefin, 7.1 Paraffin, 74.4	 $C_{10}H_{18}$	 $C_{10}H_{12}$	 $C_{11}H_{10}$
Boiling range, °F	108 to 546	367 to 395	390 to 423	440 to 461
Volumetric average boiling temperature, °F	311	375	397	454
Freezing point, °F	< -76	< -76	-40	59
Specific gravity	0.771	0.901	0.971	1.014
Viscosity, centistokes	2.67 at -40° F	13.2 at -40° F	12.7 at -40° F	2.62 at 70° F[a]
Reid vapor pressure, lb/sq in. at 60° F	5.4	Negligible	Negligible	Negligible
Hydrogen-carbon ratio	0.164	0.151	0.101	0.076
Net heat of combustion, Btu/lb	18,640	18,340	17,350	16,830
Volumetric energy content, Btu/cu ft	899,000	1,032,000	1,052,000	1,068,000
Btu/cu ft-increase over AN-F-58 fuel, percent	---------------	14.8	17.0	18.8

[a]Data unobtainable at -40° F owing to high freezing point.

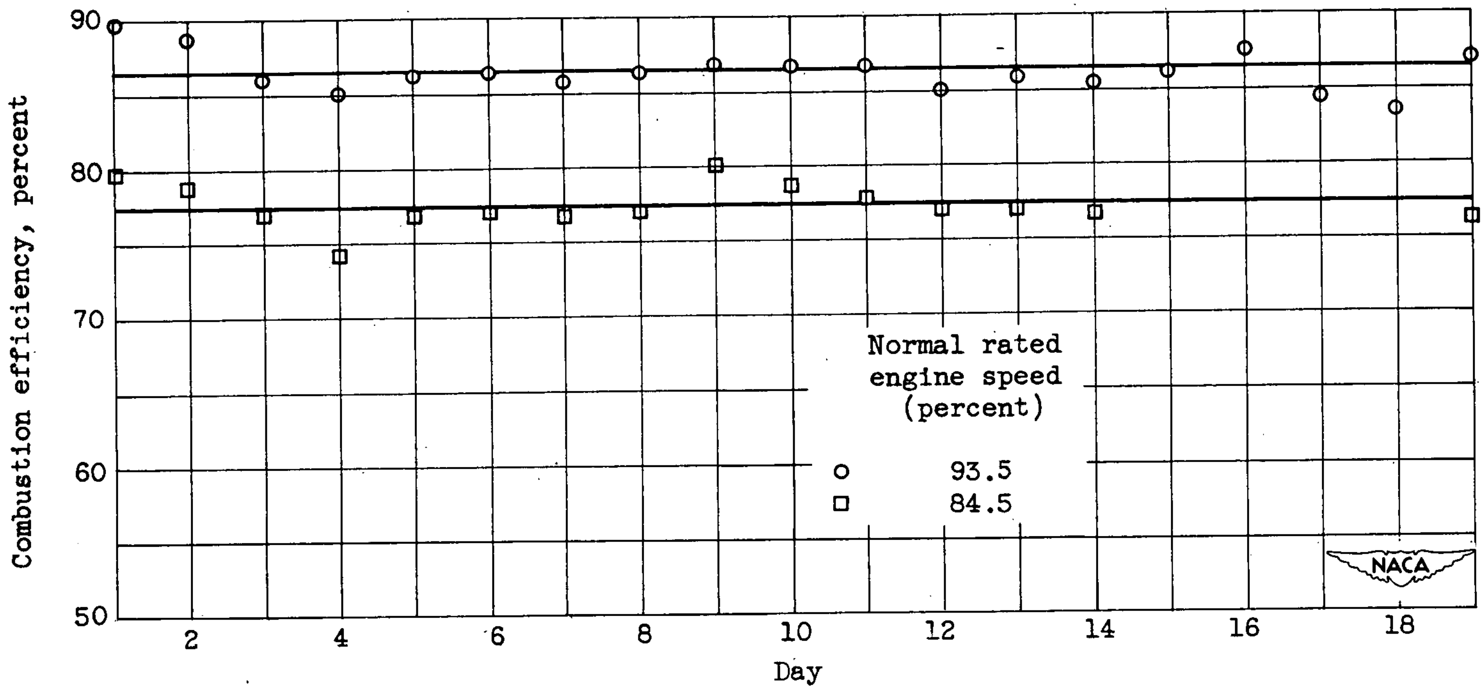
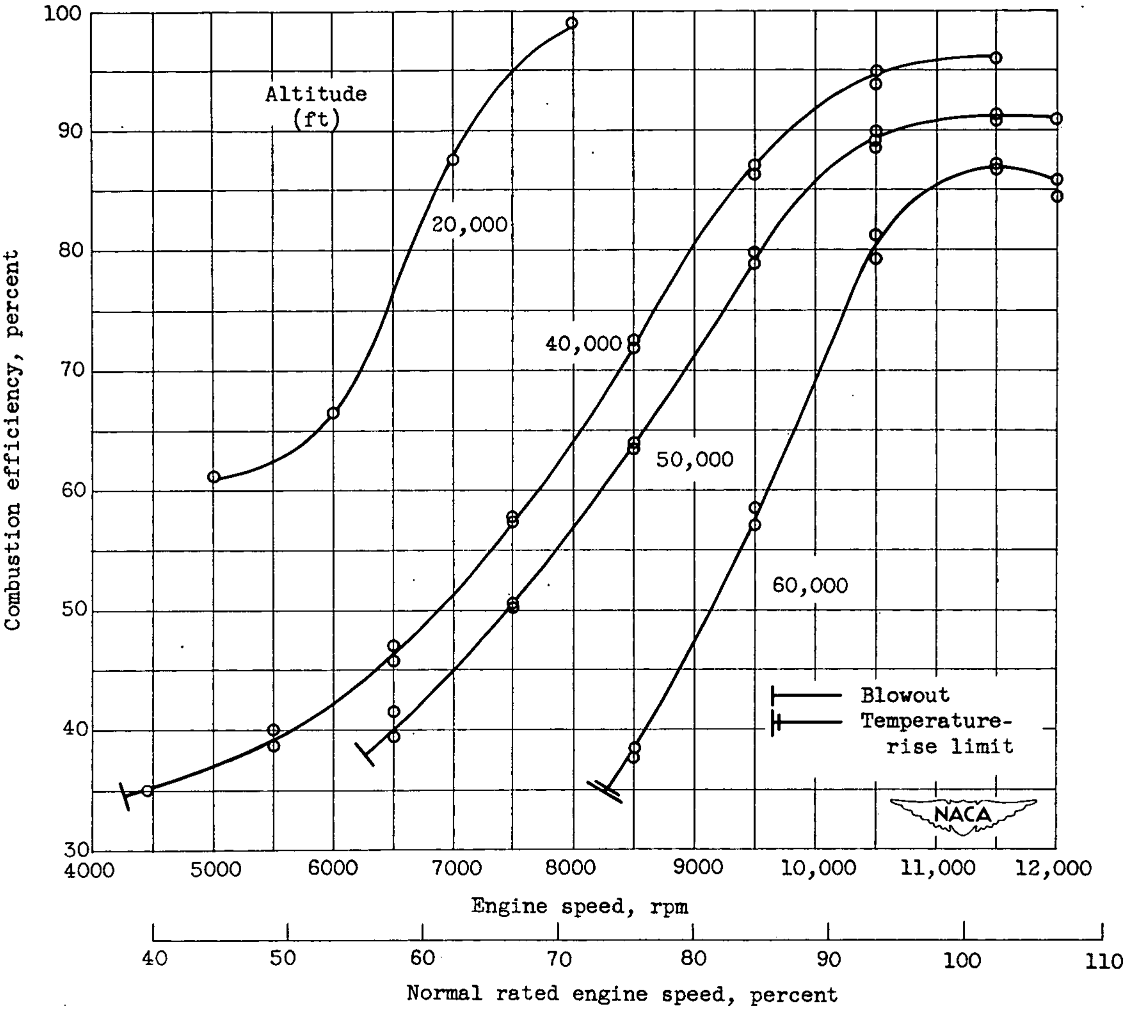
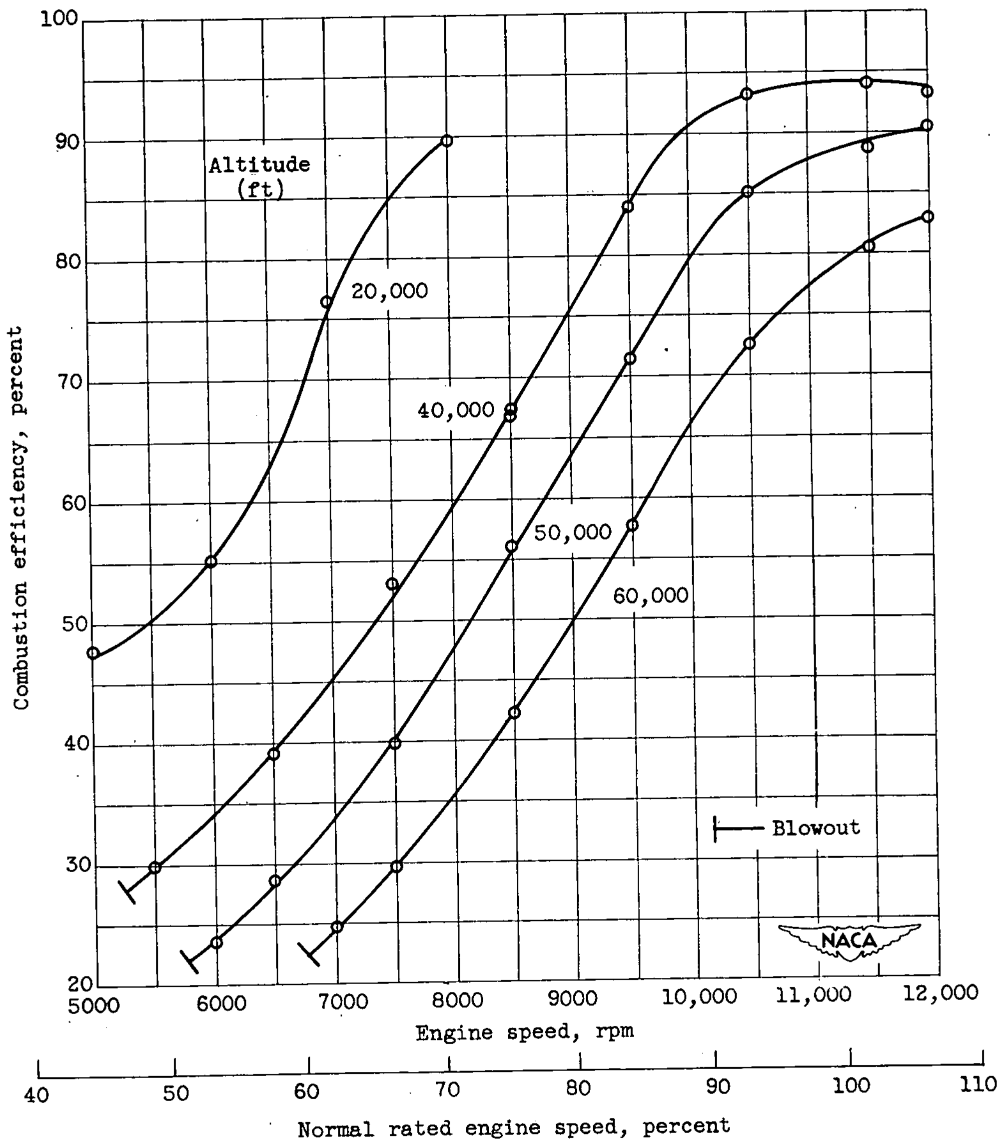


Figure 1. - Day-to-day variation in combustion efficiency with AN-F-58 fuel when used in combustor before and after tests with decalin, tetralin, and monomethylnaphthalene fuels at simulated engine operating conditions and variable temperature, pressure, and mass air flow.



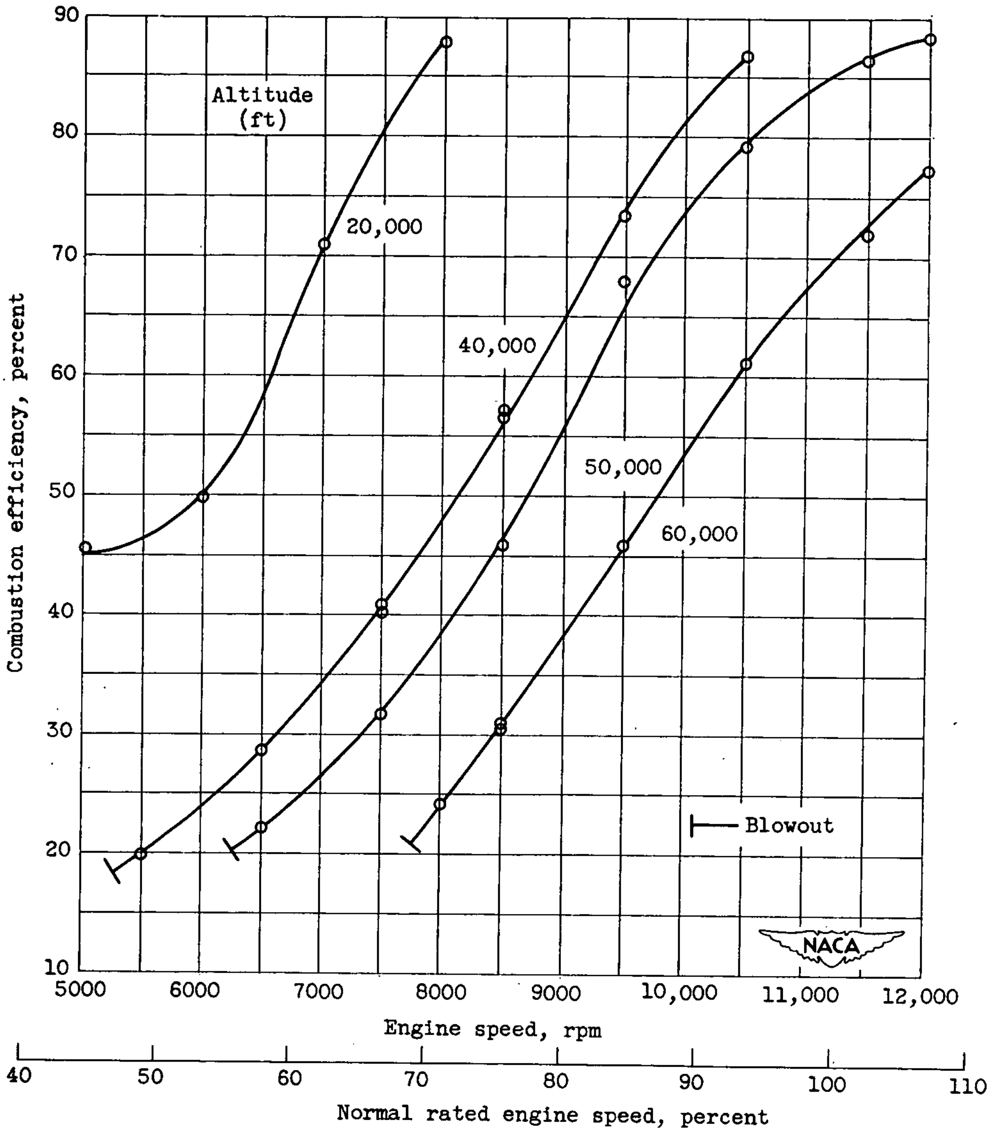
(a) Fuel, AN-F-58.

Figure 2. - Variation of combustion efficiency with engine speed and altitude in tubular combustor at flight Mach number of 0.6.



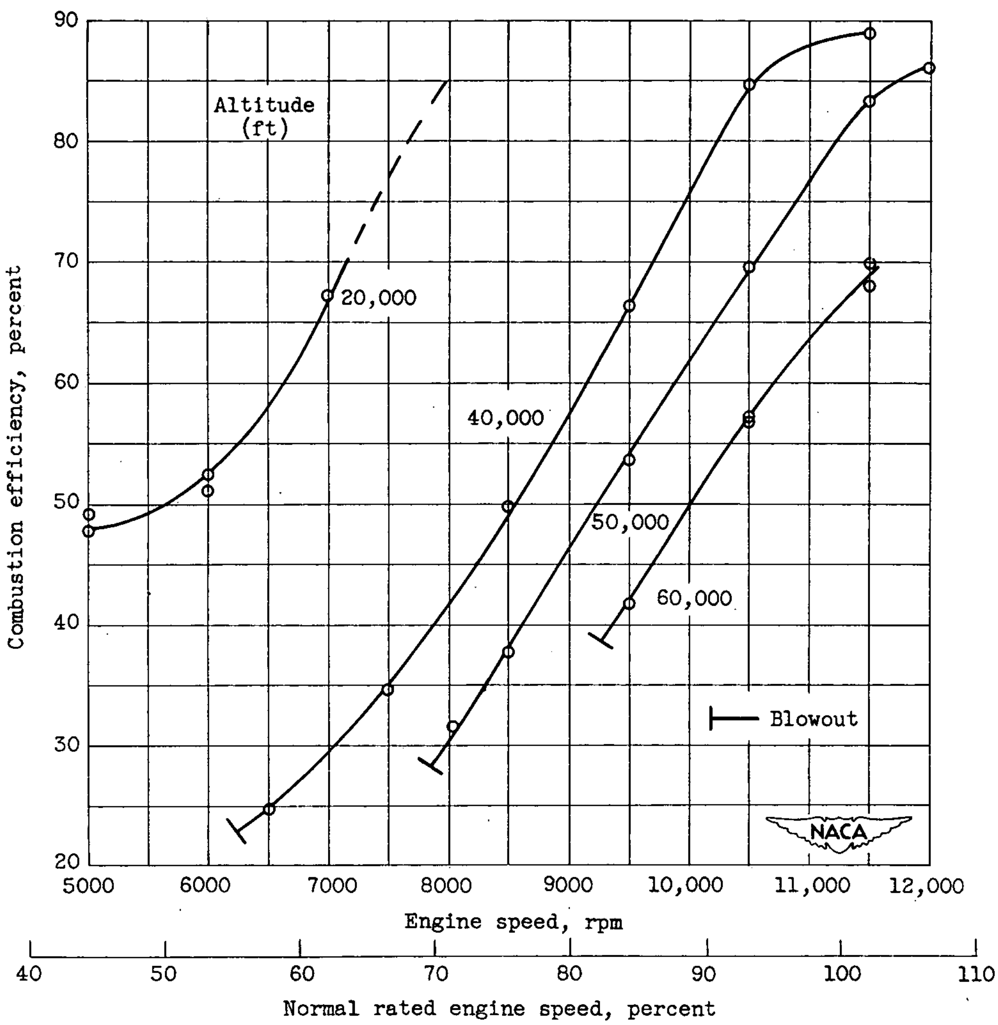
(b) Fuel, decalin.

Figure 2. - Continued. Variation of combustion efficiency with engine speed and altitude in tubular combustor at flight Mach number of 0.6.



(c) Fuel, tetralin.

Figure 2. - Continued. Variation of combustion efficiency with engine speed and altitude in tubular combustor at flight Mach number of 0.6.



(d) Fuel, monomethylnaphthalene.

Figure 2. - Concluded. Variation of combustion efficiency with engine speed and altitude in tubular combustor at flight Mach number of 0.6.

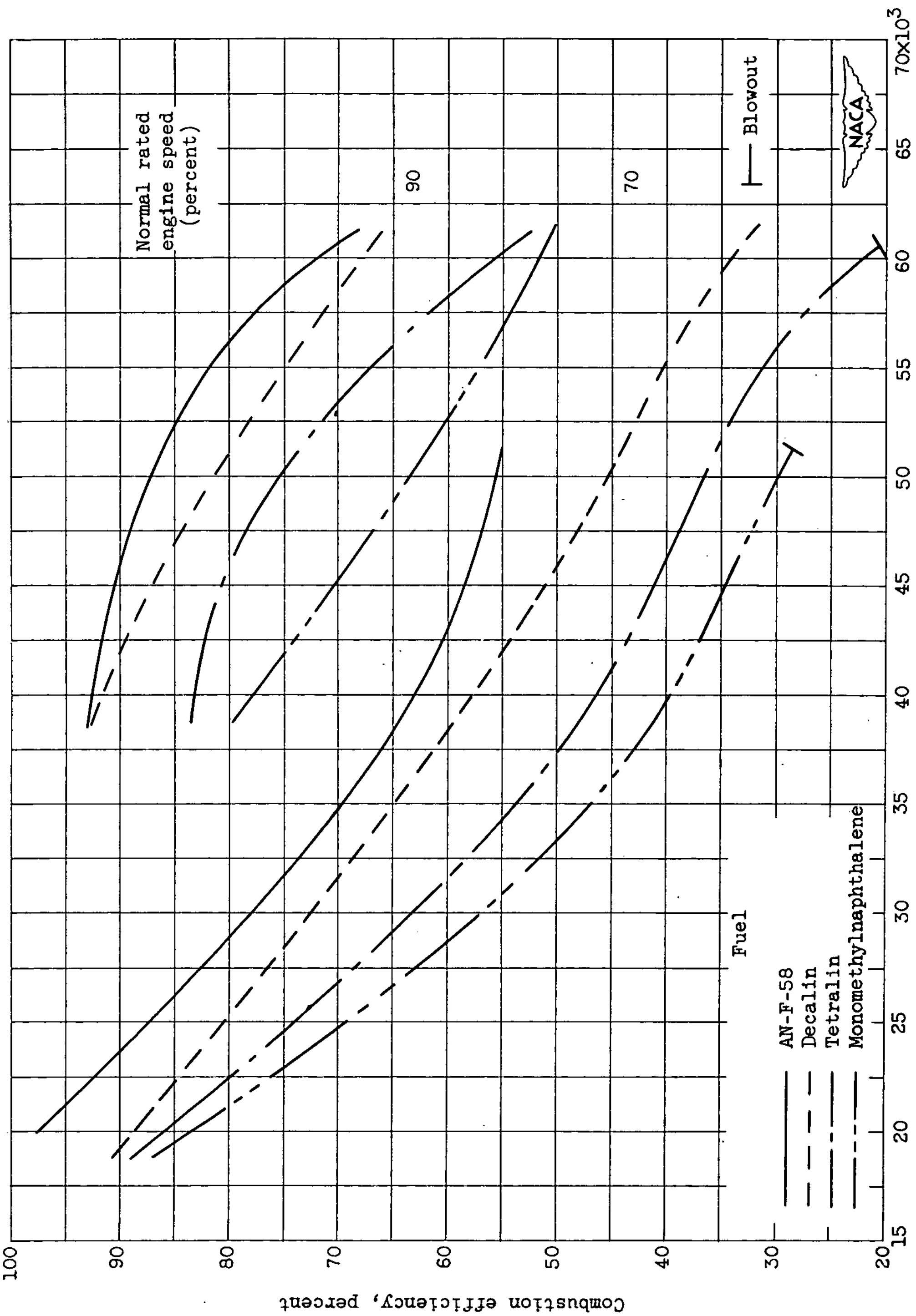


Figure 3. - Effect of altitude on combustion efficiency for four fuels in tubular combustor at 70- and 90-percent normal rated engine speed and flight Mach number of 0.6.

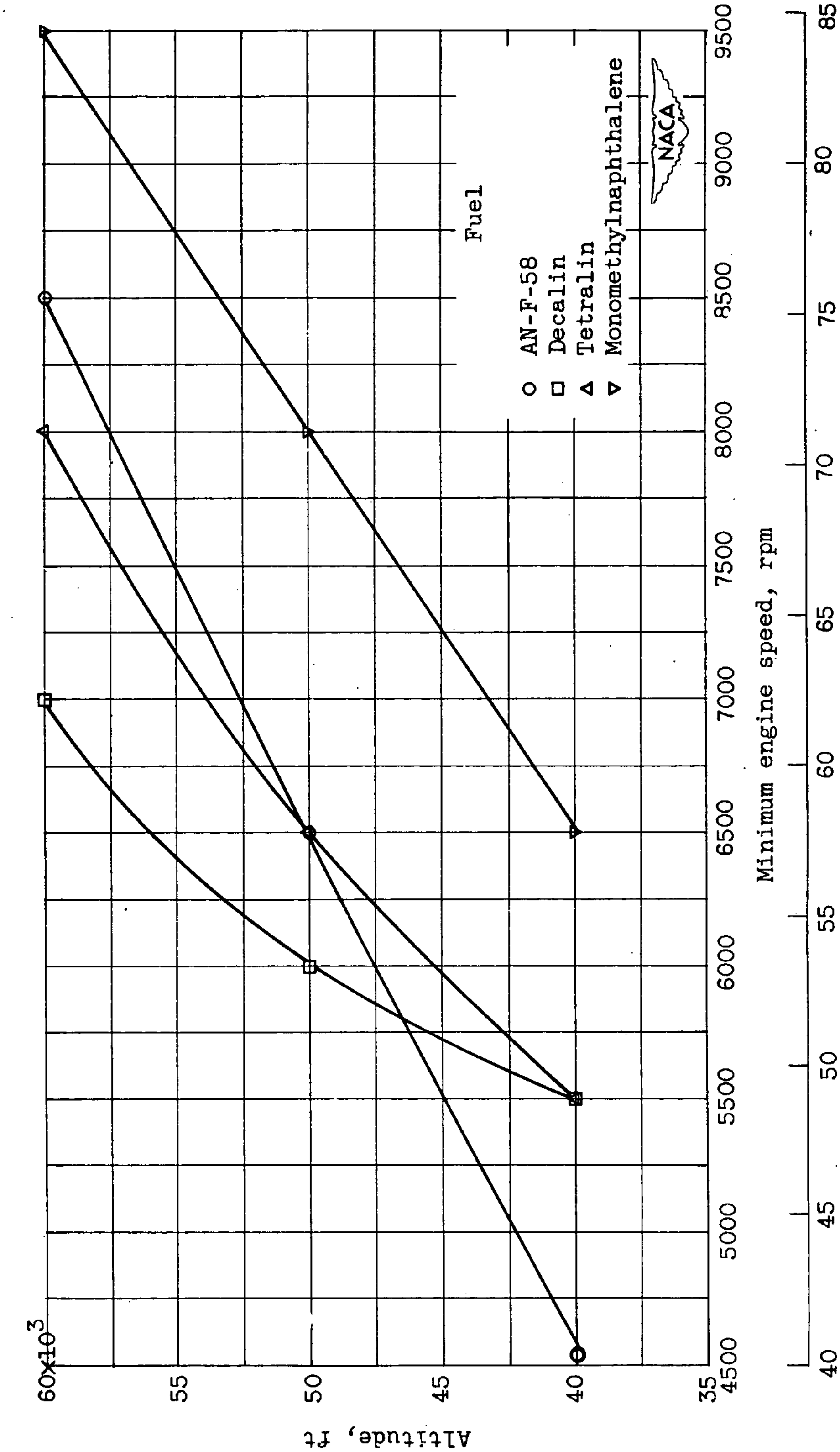


Figure 4. - Altitude operational limits for four fuels in tubular combustor at flight Mach number of 0.6.

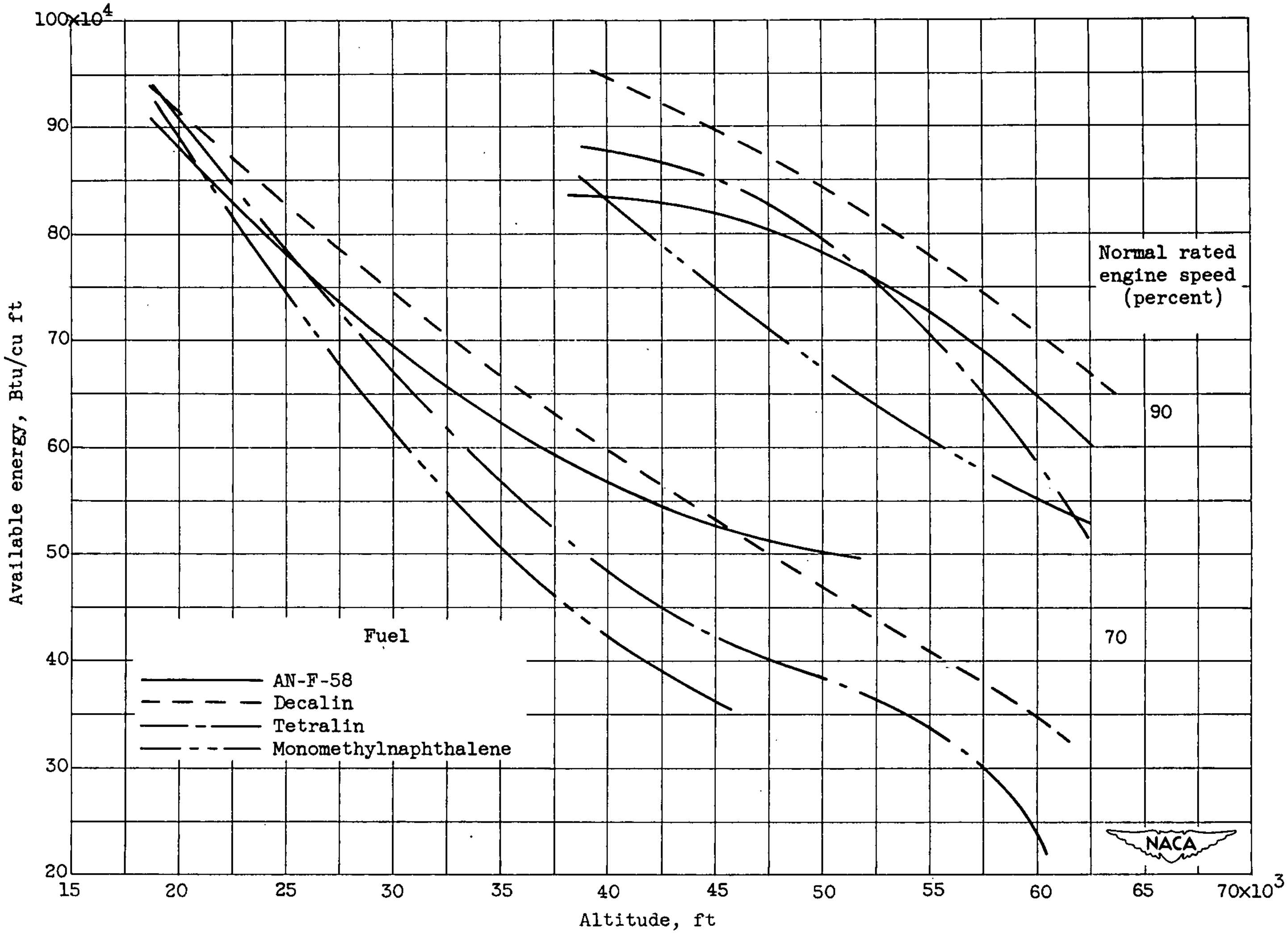


Figure 5. - Effect of altitude on available energy for four fuels in tubular combustor at 70- and 90-percent normal rated engine speed and flight Mach number of 0.6.

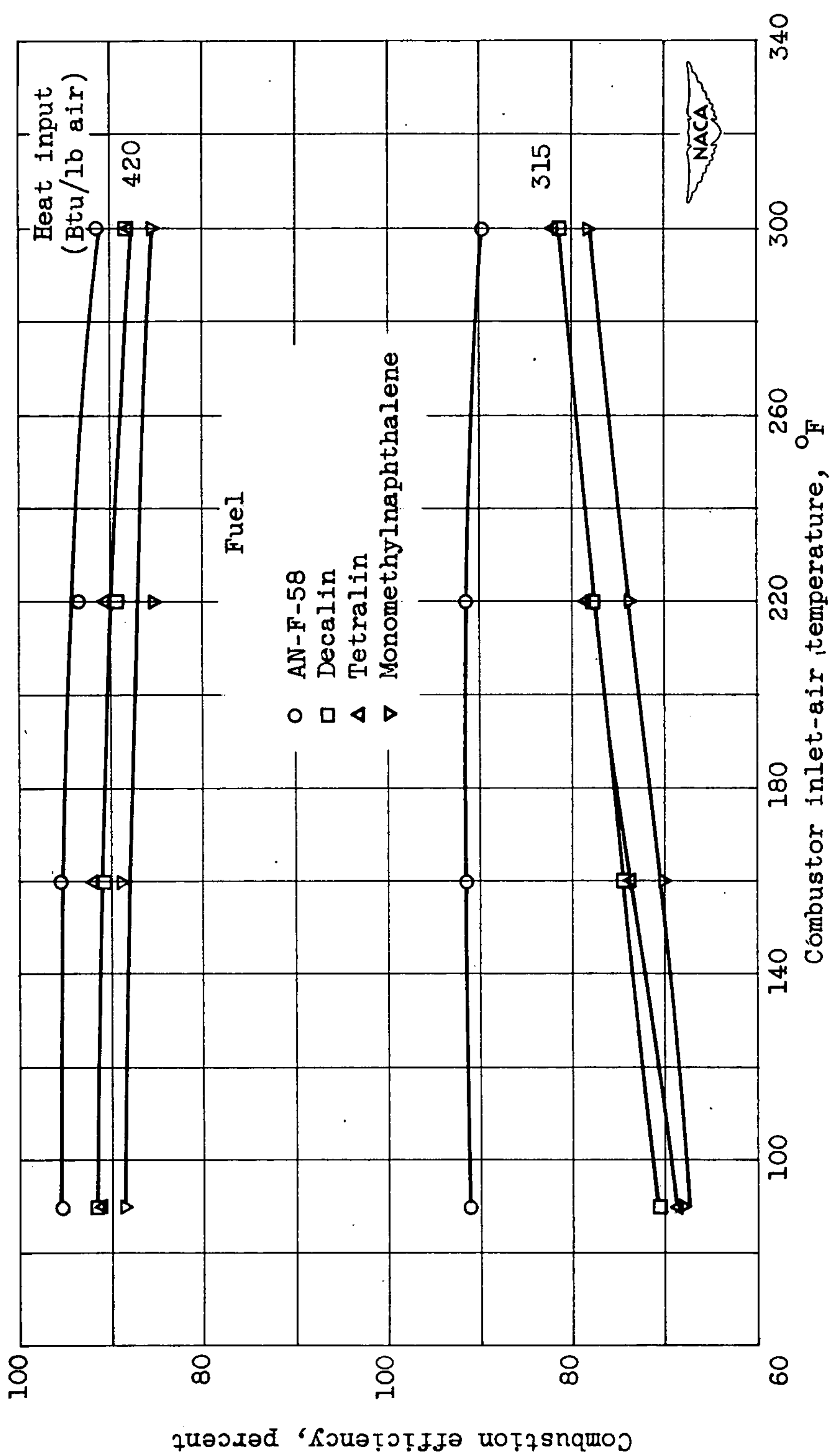


Figure 6. - Variation of combustion efficiency with combustor inlet-air temperature and heat input for four fuels in tubular combustor. Inlet-air pressure, 30.5 inches mercury absolute; mass air flow, 3.75 pounds per second per square foot.

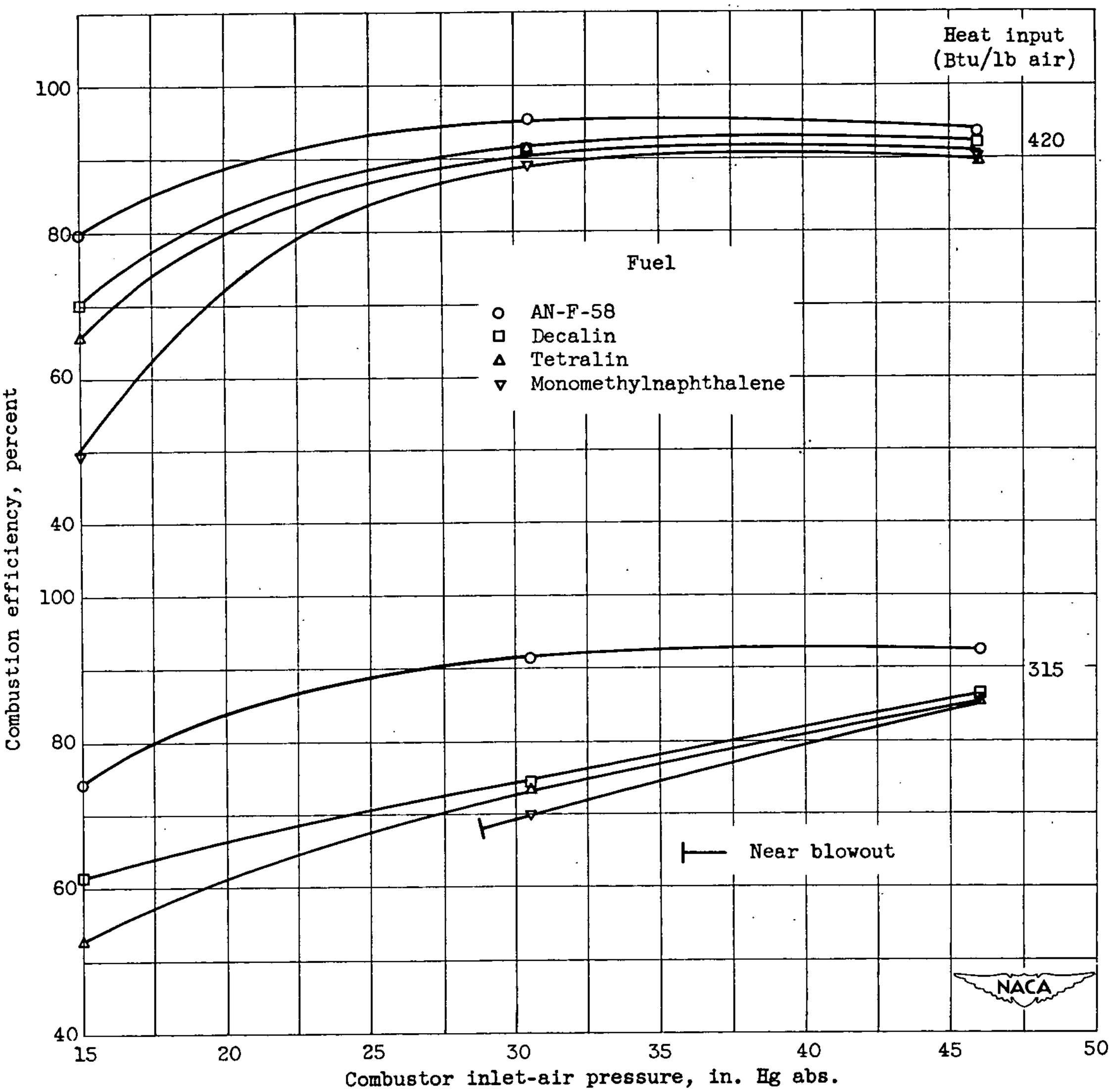


Figure 7. - Variation of combustion efficiency with combustor inlet-air pressure and heat input for four fuels in tubular combustor. Inlet-air temperature, 160° F; mass air flow, 3.74 pounds per second per square foot.

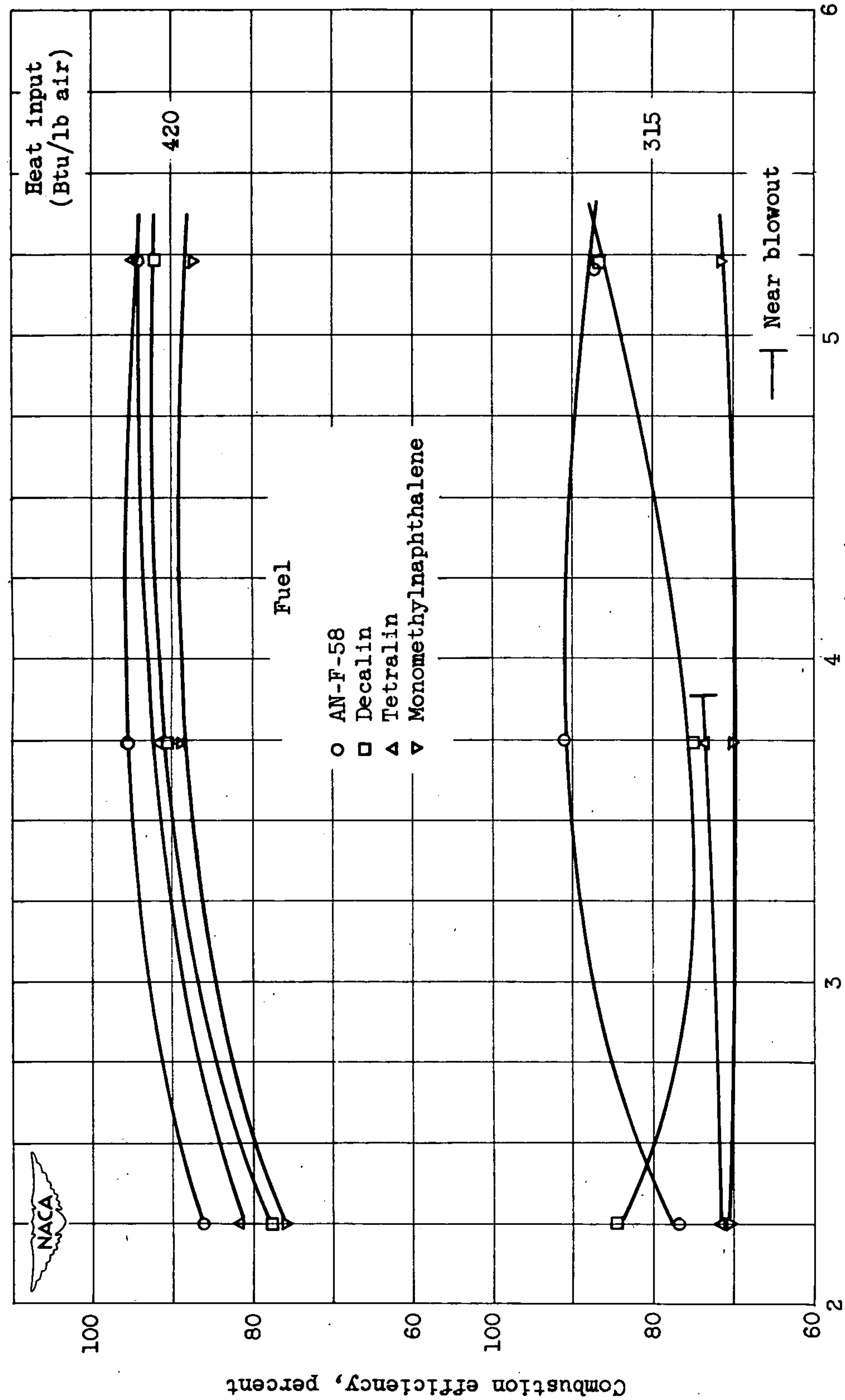


Figure 8. - Variation of combustion efficiency with mass air flow and heat input for four fuels in tubular combustor. Inlet-air pressure, 30.5 inches mercury absolute; inlet-air temperature, 160° F.