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RESEARCH MEMORANDUM

COMBUSTION-EFFICIENCY AND ALTITUDE-LIMIT INVESTIGATIONS OF FIVE FUELS IN AN ANNULAR TURBOJET COMBUSTOR

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SUMMARY

Five fuels of various boiling temperatures and various hydrocarbon types were investigated in a jet-propulsion annular combustor of $10\frac{3}{8}$-inch diameter to determine the effect of fuel boiling temperature and paraffinic and aromatic hydrocarbon types on combustion efficiency and altitude operational limit.

The fuels used in this investigation were commercial isoheptane, AN-F-28R, AN-F-32, benzene, and aromatic solvent. Commercial isoheptane, AN-F-28R, and AN-F-32 were considered paraffinic fuels with low, medium, and high boiling temperatures, respectively. Benzene and aromatic solvent were considered aromatic fuels with low and high boiling temperatures, respectively.

At the severe inlet-air condition (unstable combustion), the highest combustion efficiencies were obtained with the paraffinic and aromatic fuels with low boiling temperatures (isoheptane and benzene) and were found to vary from 30 to 58 percent. At the moderate inlet-air condition (intermediately stable combustion), the paraffinic fuels with low and medium boiling temperatures (isoheptane and AN-F-28R) gave the highest combustion efficiencies, which varied from 70 to 95 percent. The maximum variation of altitude operational limit among the fuels was 5000 feet.

INTRODUCTION

An investigation to determine the effect of fuel boiling temperature and hydrocarbon type on combustion efficiency in jet-propulsion engine combustors was conducted at the NACA Cleveland laboratory.

Investigation of several fuels in tubular combustors (references 1 and 2) has indicated that at severe operating conditions the combustion efficiency decreases as the boiling temperature of the fuel increases.

Results reported in reference 3 indicate that as the combustor from an engine is operated at increasingly higher altitudes, combustion becomes less efficient until the combustor-outlet gas temperature is insufficient for engine operation or until combustion ceases.

The investigation reported herein was made to determine the effect of fuel boiling temperature and paraffinic and aromatic type hydrocarbons on combustion efficiencies for a wide range of inlet-air conditions and the effect on the altitude operational limit of the fuels. The investigations were made on a $10\frac{3}{8}$-inch-diameter annular combustor.

APPARATUS AND INSTRUMENTATION

A diagram of the general arrangement of the combustor and the auxiliary equipment is shown in figure 1. Air flow to the combustor was measured by a square-edge orifice installed according to A.S.M.E. specifications and located upstream of all regulating valves. The combustor-inlet air temperature was regulated by an electrical heater. The combustor-inlet air quantities and pressures were regulated by remote-control valves in the laboratory air-supply and exhaust systems.

A diagrammatic cross section of the combustor and the auxiliary ducting, position of instrumentation planes, and location of temperature- and pressure-measuring instruments in the instrumentation planes is presented in figure 2. The combustor occupies the annular space around the compressor-turbine shaft of a turbojet engine. Observation windows were installed at several locations for visual inspection of the combustion. Air is admitted into the combustion zone by means of an annular basket perforated with longitudinal rows of holes. Thermocouple junctions and total-pressure taps in each instrumentation plane were located at centers of equal areas. Construction details of the temperature- and pressure-measuring instruments are shown in figure 3.

Fuel was injected into the combustor by 12 centrifugal, hollow-cone fuel nozzles with 80-degree spray angles that were equally spaced on a common manifold. Each nozzle has a rated capacity of 6 gallons per hour at a manifold pressure differential of 100 pounds per square inch. Fuel flows to the combustor were measured by rotameters calibrated for each fuel.

Pressure data were obtained by water and mercury manometers. Thermocouples were connected through multiple switches to two calibrated, self-balancing potentiometers, one with a -100° to 700° F range to record the inlet temperatures (section A-A, fig. 2) and one with a 0° to 2400° F range to record the outlet temperatures (section B-B, fig. 2).

FUELS

The fuels used in this investigation were commercial isoheptane, AN-F-28R, AN-F-32, benzene, and aromatic solvent. Commercial isoheptane, AN-F-28R, and AN-F-32 were considered as paraffinic fuels with low, medium, and high boiling temperatures, respectively. Benzene and aromatic solvent were considered aromatic fuels with low and high boiling temperatures, respectively. The AN-F-28R and AN-F-32 were considered as paraffinic fuels inasmuch as data reported in reference 1 show very little difference in the effect on combustion efficiency of paraffinic, olefinic, and naphthenic hydrocarbons.

Laboratory inspection data of the fuels are listed in the following table:

Fuel	A.S.T.M. distillation temperature (°F)			Aromatic content (volume percent)	Hydrogen-carbon ratio	Lower heating value (Btu/lb)	Specific gravity
	Initial	50-percent evaporated	Final				
Paraffinic							
Commercial isoheptane	170	180	206	0	0.177	18,900	0.727
AN-F-28R, batch 2	114	222	336	15	.176	18,700	.725
AN-F-32	330	370	462	11	.168	18,550	.797
Aromatic							
Benzene	170	172	174	100	0.088	17,400	0.877
Aromatic solvent	310	328	362	99	.115	17,600	.873

PROCEDURE

Combustion Efficiency

The combustion efficiencies of the fuels were determined at the three following arbitrarily chosen inlet-air conditions, representing the range encountered with conventional compressor-turbine units; inlet-air conditions 1, 2, and 3 were characterized as severe (unstable combustion), moderate (intermediately stable combustion), and favorable (stable combustion), respectively:

Inlet-air condition	Inlet-air total pressure (in. Hg absolute)	Inlet-air total temperature (°F)	Specific mass air flow[a] (lb/sec-sq ft)
1	14.3	40	2.15, 2.53, 2.91
2	30.7	160	3.83, 4.50, 5.18
3	51.1	250	6.01, 7.07, 8.13

[a] Inlet-air flow based on combustor maximum cross-sectional area of 0.503 sq ft measured 12 in. downstream of section A-A, (fig. 2).

The fuel-air mixture in the combustor was ignited by an ignition plug (fig. 2); after combustion was started, the ignition plug was deenergized. At any desired set of combustor inlet-air conditions, the appropriate inlet-air temperature, pressure, and mass air flow were established at a low fuel flow. From that condition, the fuel flow was gradually increased until local combustor-outlet temperatures (sec. B-B, fig. 2) of approximately 1800° F were reached or blow-out occurred. An approximate average combustor temperature rise of 1200° F was possible with a limit of 1800° F on local combustor-outlet temperatures. A local combustor-outlet temperature exceeding 1800° F was considered unsafe for the instrumentation.

Altitude Operational Limit

Combustor-inlet and combustor-outlet conditions used for investigating the altitude operational limits of the fuels were obtained from the manufacturer's performance estimates of a compressor-turbine unit using an annular combustor. At each simulated rotational speed and altitude condition, the fuel flow was increased from the starting fuel flow in an effort to obtain an average combustor-outlet temperature equal to or greater than that required for engine operation at the same conditions. The highest simulated altitude at any one simulated rotational speed for which the required average combustor-outlet temperature could be obtained was designated the altitude operational limit of the fuel for this combustor at the simulated rotational speed.

CALCULATIONS

The performance of the fuels was evaluated by means of data from instruments located at sections A-A and B-B (fig. 2).

The average reading of the two thermocouples located in section A-A was used as the inlet-air total temperature; the inlet-air total-pressure values were averages of the readings of the six total-pressure tubes located in section A-A. At section B-B, the average reading of the 36 thermocouples was used as the average combustor-outlet gas total temperature, taking the thermocouple readings as true values of the total temperature.

Average combustor temperature rise was taken as the average combustor-outlet total temperature (section B-B) minus the average combustor-inlet total temperature (section A-A). Combustion efficiency is arbitrarily defined as the ratio of the theoretical weight of fuel required for the observed average combustor temperature rise to the actual weight of fuel consumed for the observed average combustor temperature rise. Computations of theoretical fuel-air ratios were made from figure 5 of reference 4.

In order to place the performance of the various fuels on a comparable basis, heat input (product of fuel-air ratio and lower heating value of the fuel) is used in place of fuel-air ratio on the plots.

RESULTS AND DISCUSSION

Combustion Efficiency

Investigation of each fuel was repeated at the intermediate air-flow condition of the three inlet-air conditions to determine the reproducibility of the data. The two investigations with any one fuel were made on different days with intervening investigations. The two sets of data for any one fuel were used for fairing the curve. The repeated investigations are represented by single-tail data points.

Inlet-air condition 1. - The variation of average combustor temperature rise with heat input is shown in figure 4. Lines of theoretical combustion efficiency (calculated as previously defined) are included on this plot and apply to all the fuels. Double-tail data points represent data at very unstable combustion and were not used to fair the curves.

All the fuels at the intermediate and high air-flow conditions and AN-F-28R at the low air-flow condition were limited by blow-out before an average combustor temperature rise of approximately 1200° F was obtained. Combustion became erratic as the blow-out limit was approached. Aromatic solvent was limited by blow-out at all air-flow conditions. With aromatic solvent at the low air-flow condition, the maximum average combustor temperature rise obtained was 250° F (combustion efficiency of 15 percent), therefore data for this fuel are not included on the plot.

With the exception of isoheptane at the high air-flow condition, the combustor temperature rise increased with an increase in heat input to the point of blow-out, and the combustion efficiency increased with an increase in heat input but reached a maximum before blow-out occurred.

Except at the high air-flow condition, the paraffinic fuel with a high boiling temperature (AN-F-32) gave as large a combustor temperature rise (at lower efficiency) as did the paraffinic fuel (isoheptane) and aromatic fuel (benzene) with low boiling temperatures. The highest combustion efficiencies were obtained with isoheptane and benzene and were found to vary from 30 to 58 percent, depending on heat input.

Variation of combustion efficiency among the fuels and effect of air flow on combustion efficiency are presented in figure 5. Data are cross plots of figure 4 at two values of heat input.

The paraffinic fuels with low and medium boiling temperatures (isoheptane and AN-F-28R) gave combustion efficiencies from 8 to 20 percent greater than the paraffinic fuel with a high boiling temperature (AN-F-32) at two values of heat input.

Combustion efficiencies of the fuels were decreased 7 to 26 percent with increase in air flow for the range of air flows investigated.

Inlet-air condition 2. - Combustion was stable at this inlet condition and peak temperatures limited the investigation in each case. A plot of average combustor temperature rise with heat input is presented in figure 6. The combustor temperature rise increased steadily with increase in heat input over the range investigated. With the exception of the aromatic fuel with a high boiling temperature (aromatic solvent), the combustion efficiencies of the fuels increase only slightly with increase in heat input above a combustor temperature rise of 800° F. The paraffinic fuels with low and medium boiling temperatures (isoheptane and AN-F-28R) gave the highest combustion efficiencies, which varied from 70 to 95 percent.

Data showing the variation of combustion efficiency among the fuels and the effect of air flow on combustion efficiency are presented in figure 7. For two values of heat input, isoheptane and AN-F-28R gave the highest combustion efficiencies over the range of air flows investigated.

Increasing the air flow over the range investigated had little effect on the combustion efficiencies of isoheptane and AN-F-28R; an increase in the air flow, however, raised the combustion efficiency of AN-F-32 about 6 percent and decreased the combustion efficiency of benzene 8 percent and of aromatic solvent 5 percent.

Data taken at condition 2 with intermediately stable combustion do not show as much performance difference among the fuels as data taken at condition 1 with unstable combustion.

Inlet-air condition 3. - Combustion was very stable at this condition and as in condition 2 the investigations were limited by peak temperatures.

As shown in figure 8, the combustor temperature rise increased steadily with increase in heat input. The variation of combustion efficiencies among the fuels and effect of air flow on combustion efficiency at two values of heat input are presented in figure 9. Except for aromatic solvent at the low value of heat input, the variation of the combustion efficiencies among the fuels is small, and heat input had very little effect on the combustion efficiencies of the fuels. All fuels except the aromatic solvent gave combustion efficiencies above 90 percent for the range investigated.

Increasing the air flow over the range investigated had little effect on the combustion efficiencies of any of the fuels except aromatic solvent at low values of heat input where combustion efficiency decreased 15 percent.

Altitude Operational Limit

Data showing the altitude operational limit of the various fuels at different values of percentage rated simulated engine rotational speed are presented in figure 10. Combustion efficiencies of the five fuels at their altitude operational limits are included in the figure.

The spread in altitude operational limit among the fuels for all speeds varied from approximately 2000 to 5000 feet. Although the spread in altitude limit of the fuels was small, AN-F-28R and aromatic solvent generally had the lowest altitude limits. The altitude limit of isoheptane and AN-F-32 was approximately the same at rated rotational speed, however the combustion efficiency of isoheptane was 16 percent greater than that of AN-F-32. The benzene permitted the highest altitude limit at rated simulated rotational speed.

SUMMARY OF RESULTS

From combustion-efficiency and altitude-operational-limit investigations of five fuels made in a jet-propulsion annular combustor of $10\frac{3}{8}$-inch diameter, the following results were obtained; the combustion-efficiency investigation was made at inlet-air conditions characterized as severe, moderate, and favorable:

1. At the severe inlet-air condition (unstable combustion), the highest combustion efficiencies were obtained with the paraffinic and aromatic fuels with low boiling temperatures (isoheptane and benzene) and were found to vary from 30 to 58 percent.

2. At the moderate inlet-air condition (intermediately stable combustion), the paraffinic fuels with low and medium boiling temperatures (isoheptane and AN-F-28R) gave the highest combustion efficiencies, which varied from 70 to 95 percent.

3. At the favorable inlet-air condition (stable combustion), all fuels except the aromatic fuel with a high boiling temperature (aromatic solvent) gave combustion efficiencies above 90 percent for the range investigated.

4. The spread in altitude operational limit among the fuels for all engine speeds varied from 2000 to 5000 feet with the aromatic fuel of low boiling temperature (benzene) permitting the highest altitude limit at rated engine speed. A higher altitude operational limit was permitted by AN-F-32 than by AN-F-28R.

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4. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN No. 1086, 1946.

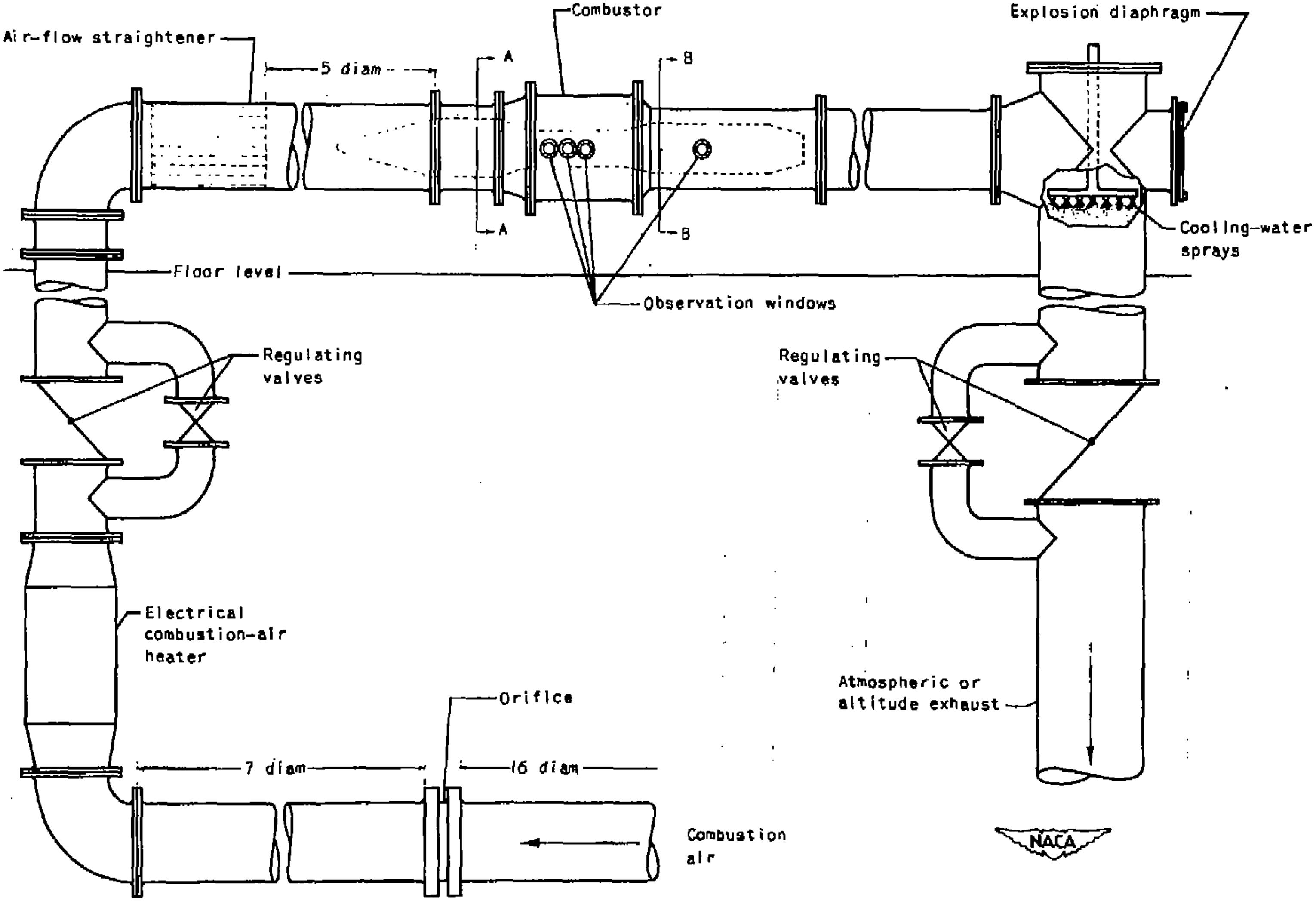


Figure 1. - Diagrammatic sketch of $10\frac{3}{8}$-inch-diameter annular combustor and auxiliary equipment. A-A, B-B, instrumentation planes.

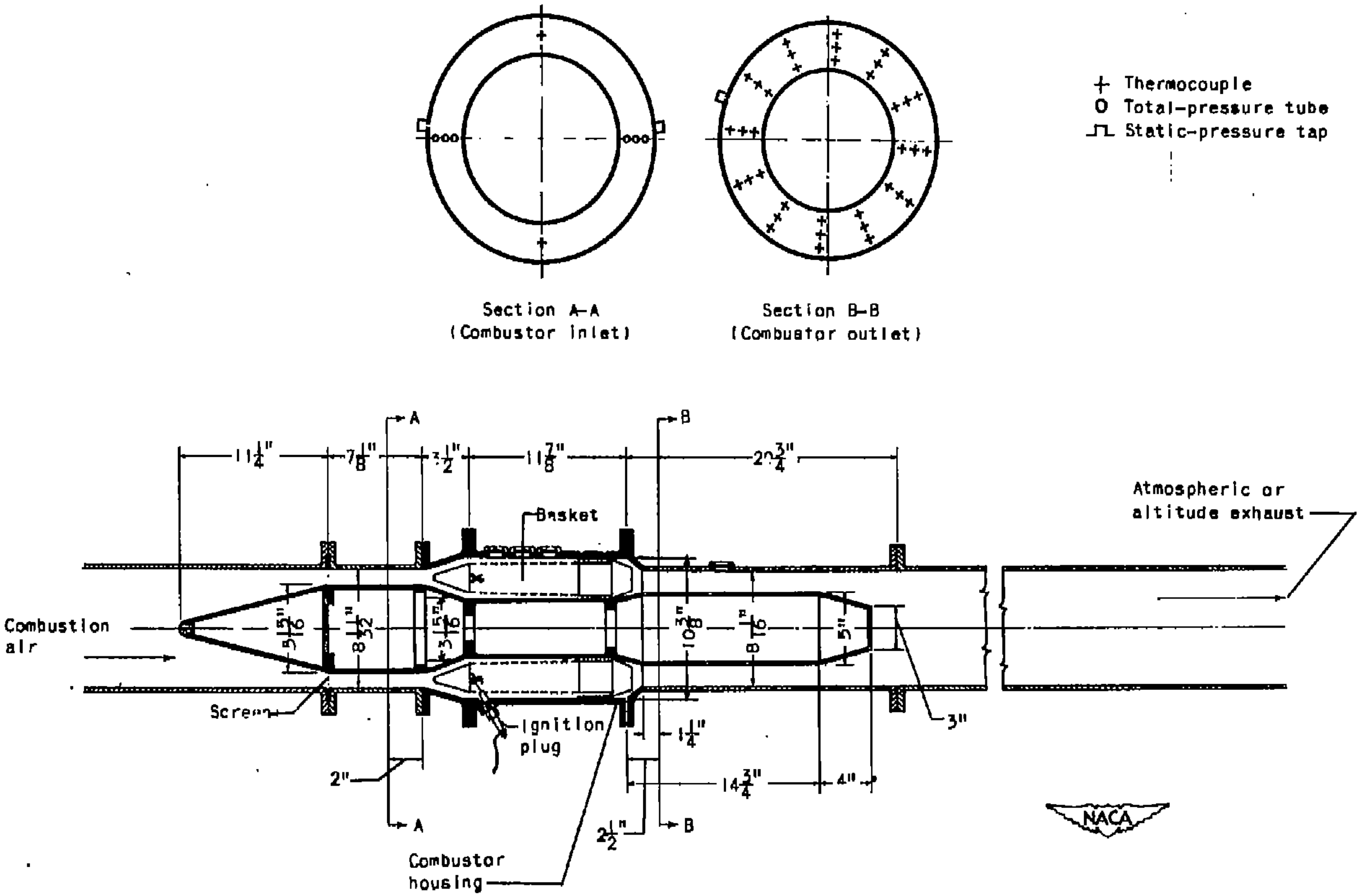
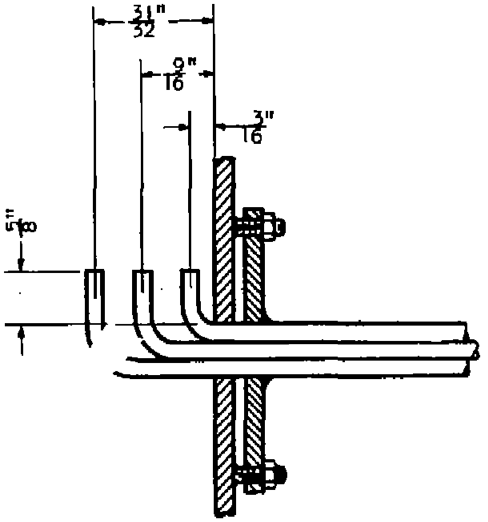
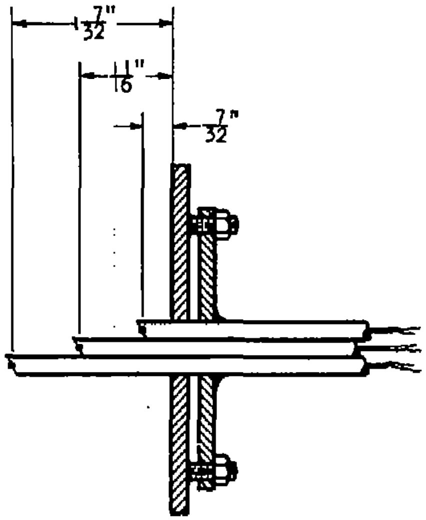


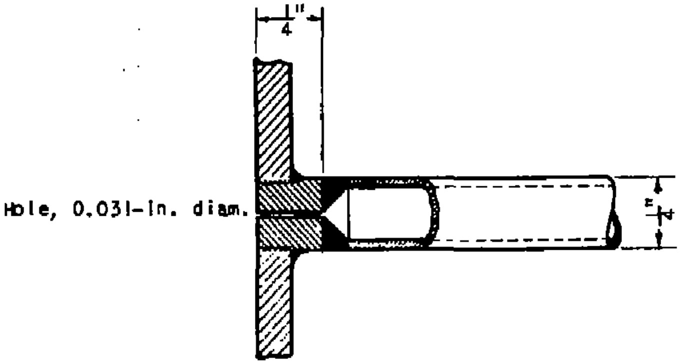
Figure 2. - Cross section of $10\frac{3}{8}$-inch-diameter annular combustor showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes.



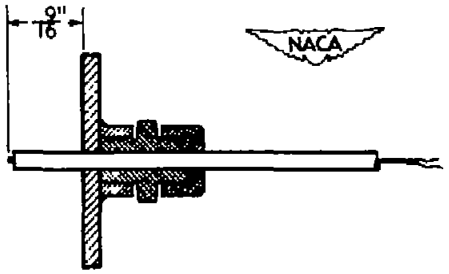
Total-pressure rake
(Section A-A)



Chromel-alumel
thermocouple bank
(Section B-B)



Static-pressure tap
(Sections A-A, B-B)



Iron-constantan
thermocouple
(Section A-A)

Figure 3. - Construction and instrumentation details of temperature- and pressure-measuring instruments.

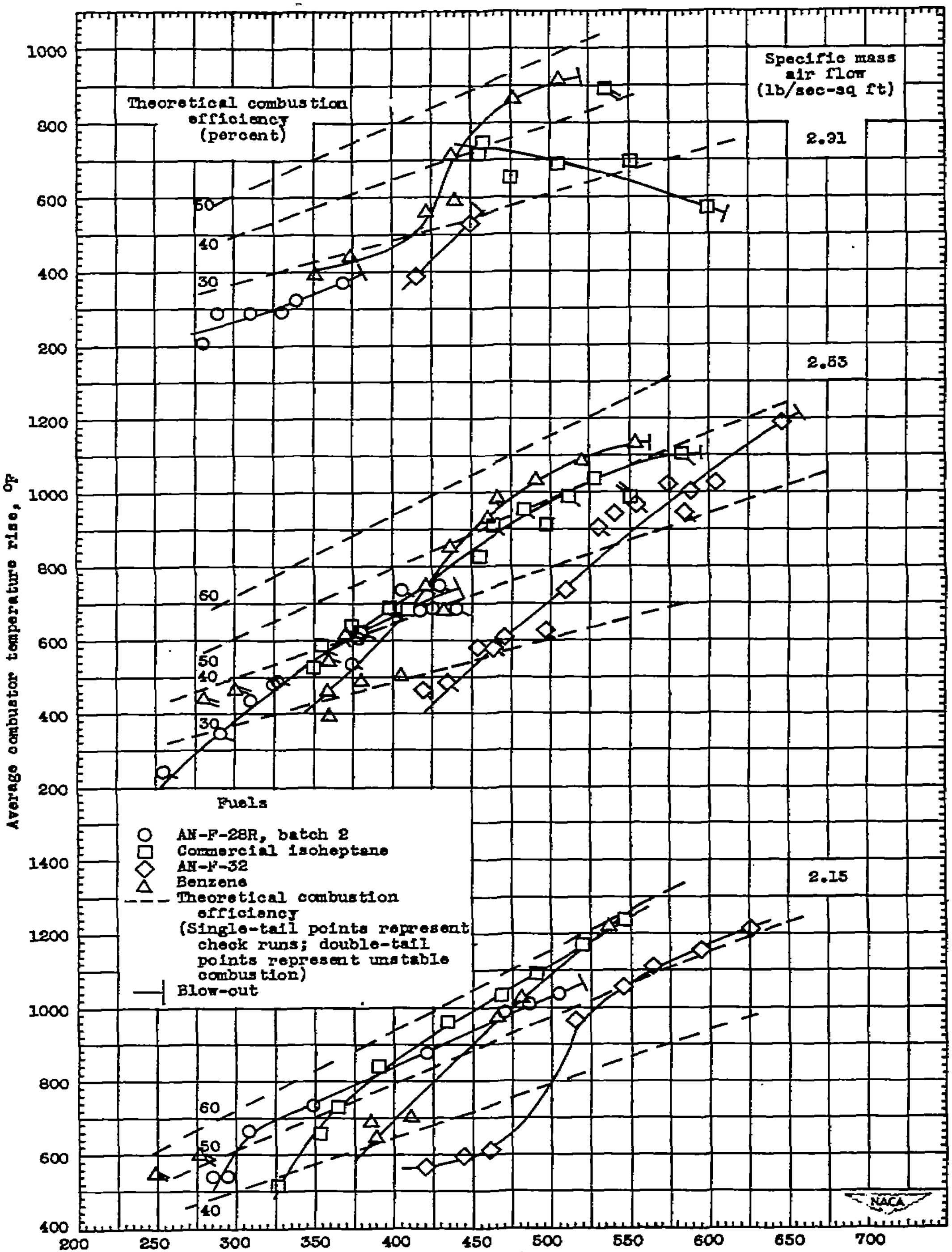


Figure 4. - Variation of average combustor temperature rise and combustion efficiency with heat input for several fuels and three values of mass air flow. Annular combustor diameter, 10$\frac{3}{8}$ inches; inlet-air total pressure, 14.3 inches mercury absolute; inlet-air total temperature, 40° F.

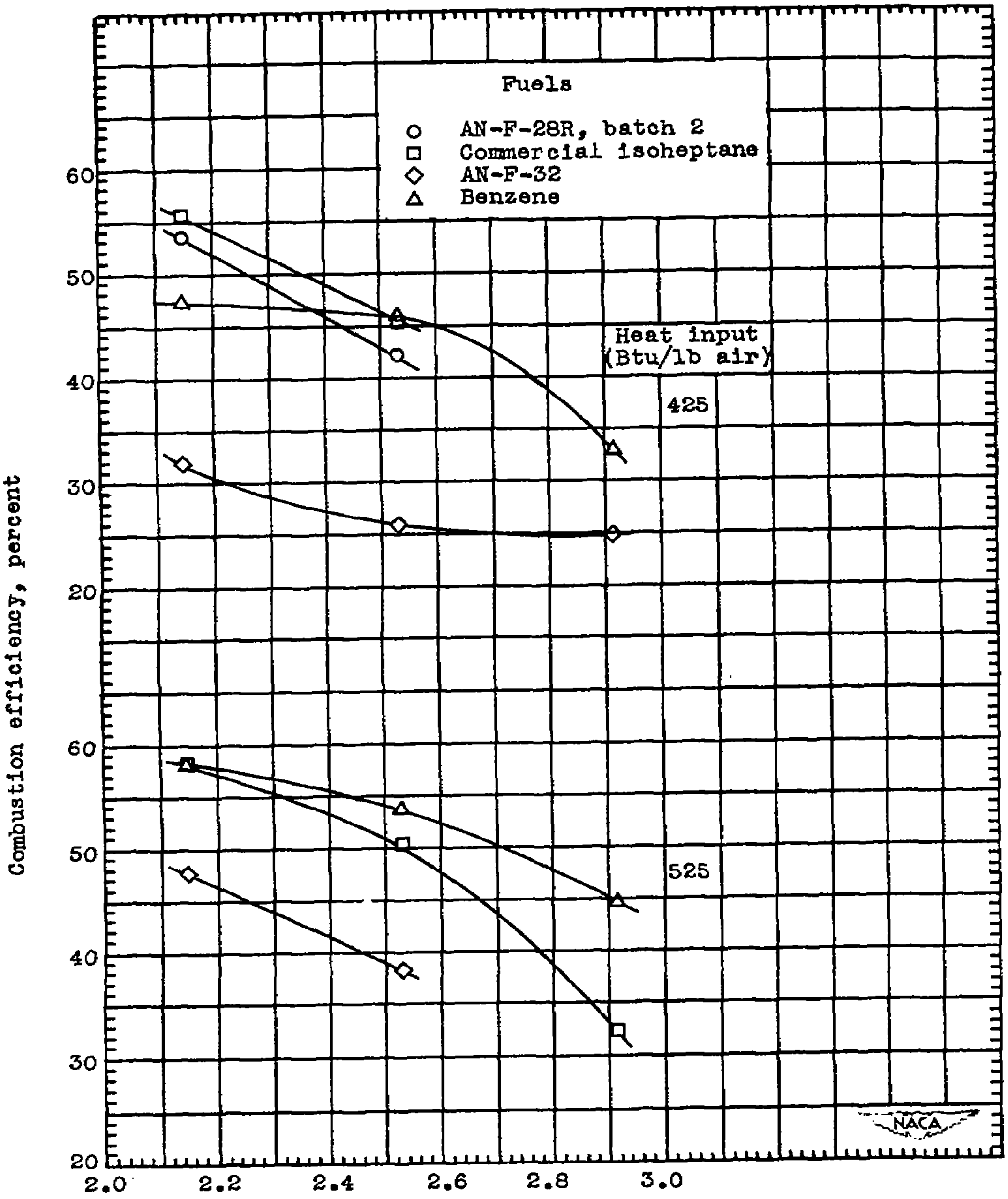


Figure 5. - Relation of combustion efficiency to mass air flow for several fuels at two values of heat input. Annular combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 14.3 inches mercury absolute; inlet-air total temperature, 40° F.

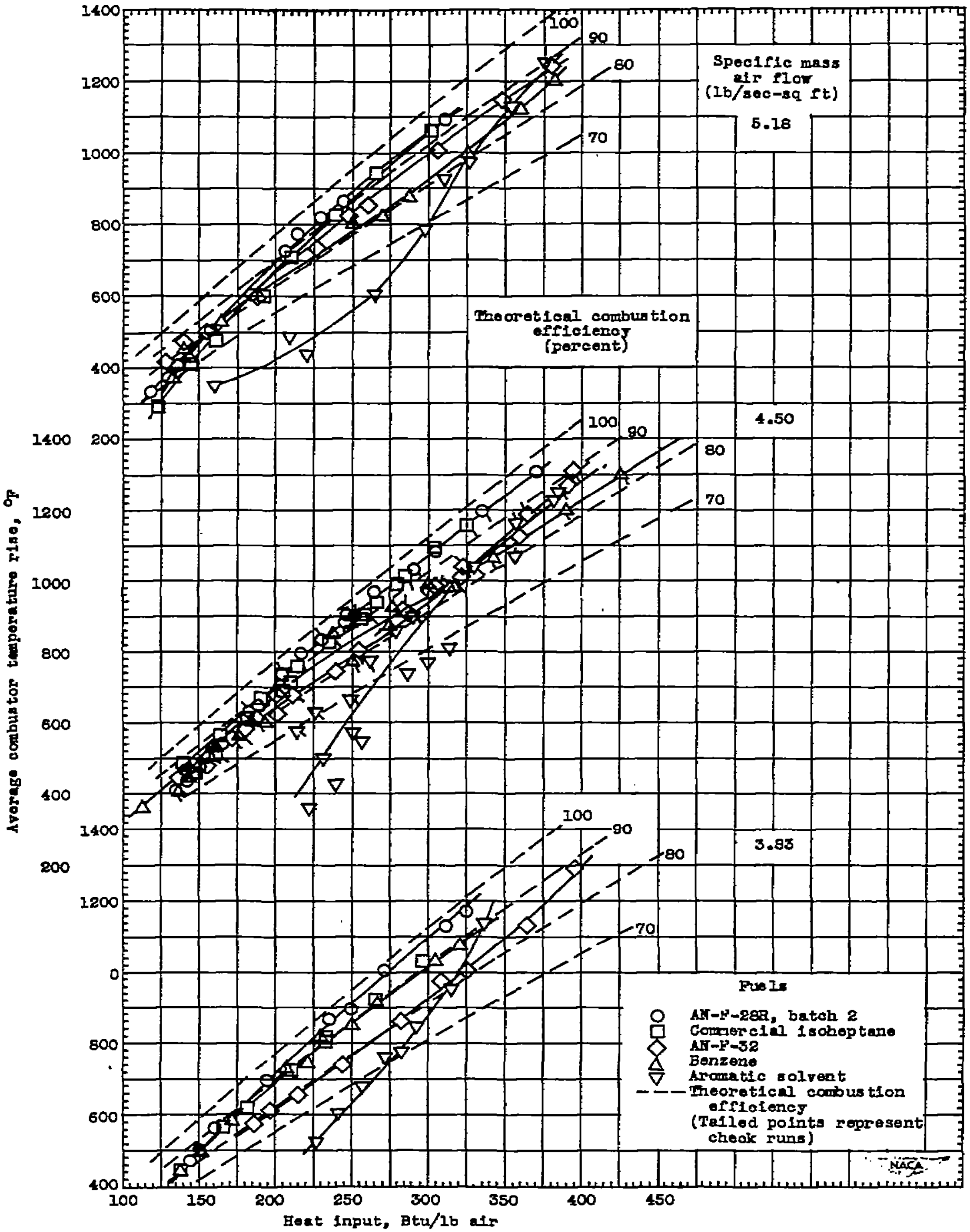


Figure 6. - Variation of average combustor temperature rise and combustion efficiency with heat input for several fuels and three values of mass air flow. Annular combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 30.7 inches mercury absolute; inlet-air total temperature, 160° F.

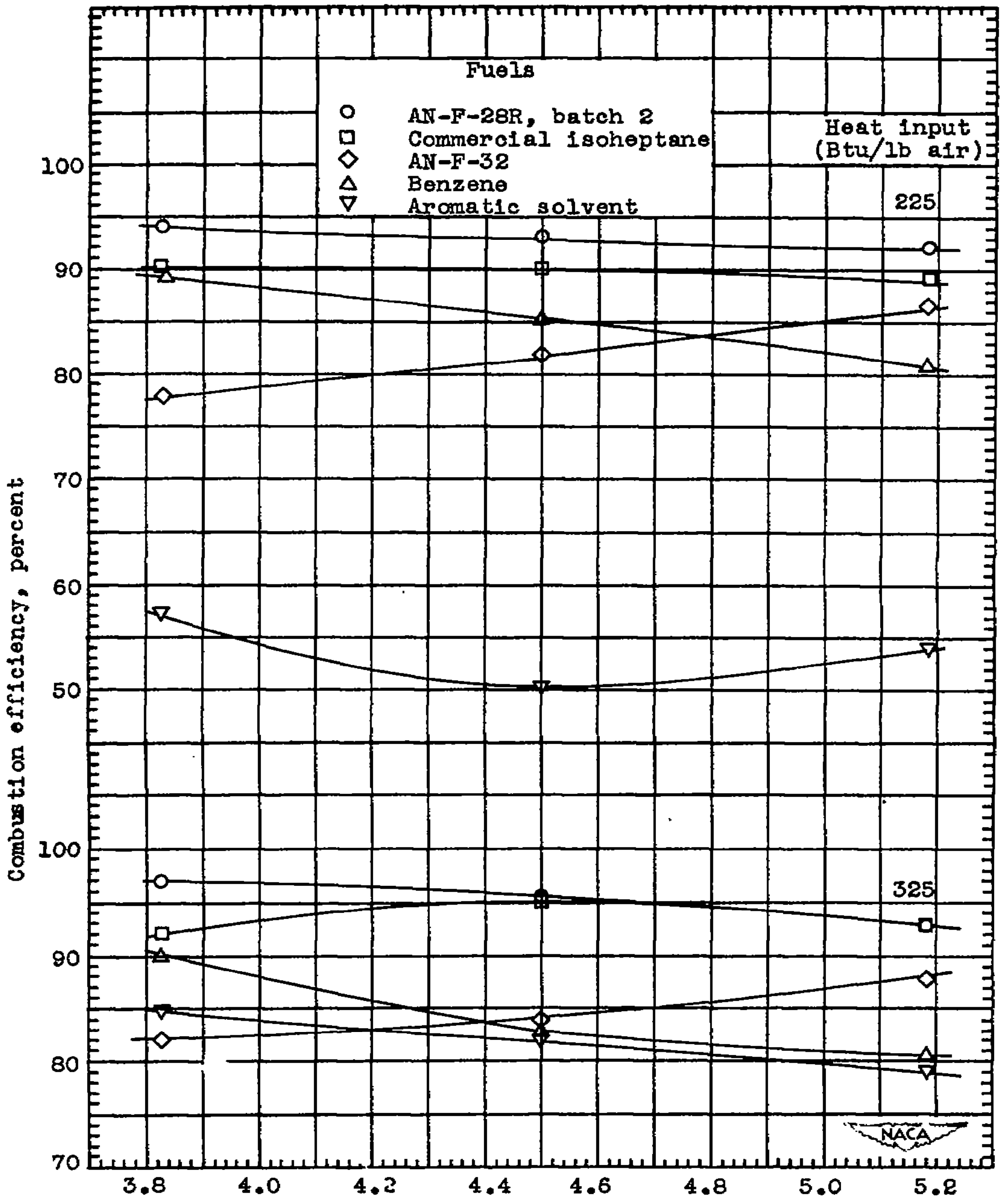


Figure 7. - Relation of combustion efficiency to mass air flow for several fuels at two values of heat input. Annular combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 30.7 inches mercury absolute; inlet-air total temperature, 160° F.

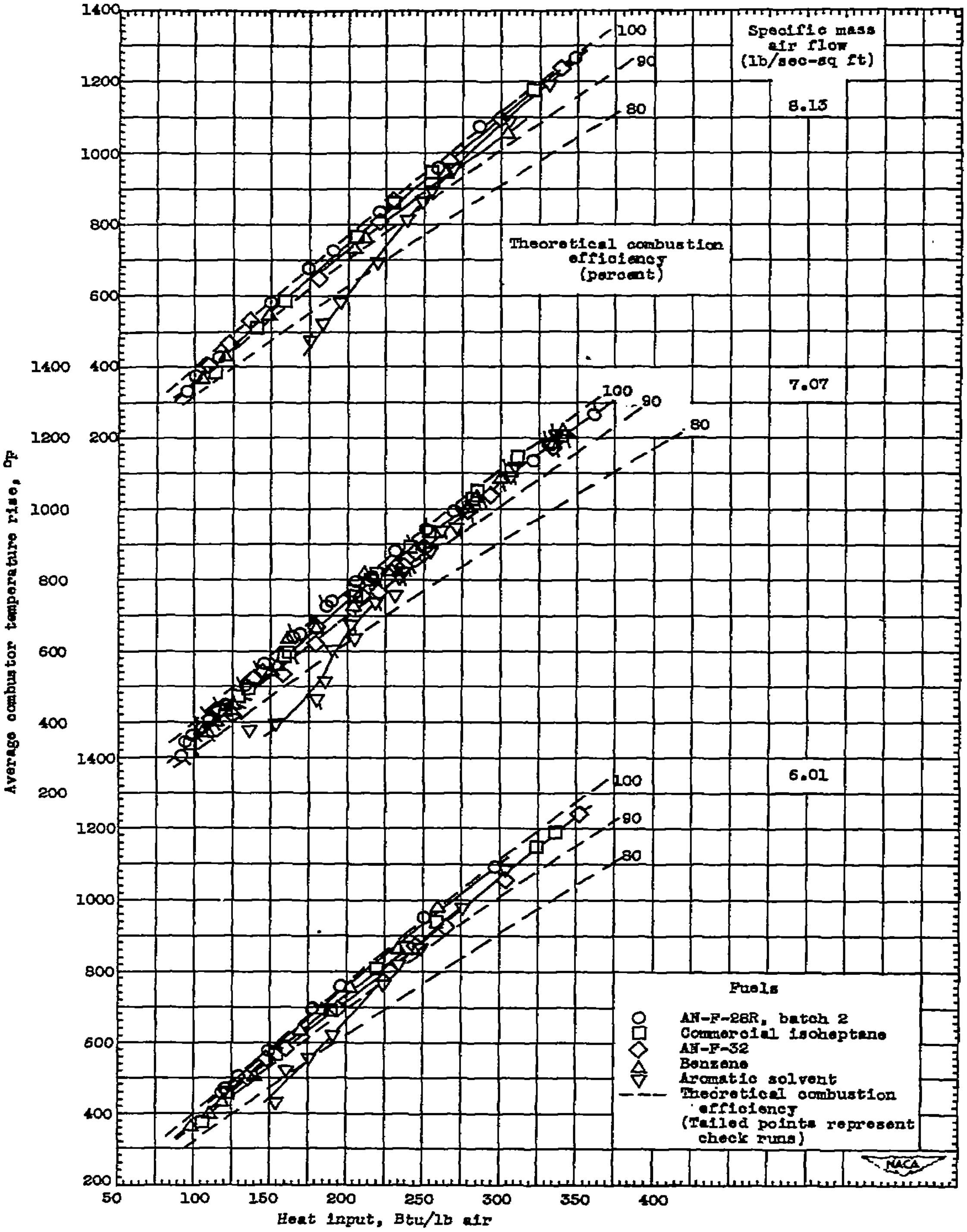


Figure 8. - Variation of average combustor temperature rise and combustion efficiency with heat input for several fuels and three values of mass air flow. Annular combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 51.1 inches mercury absolute; inlet-air total temperature, 250° F.

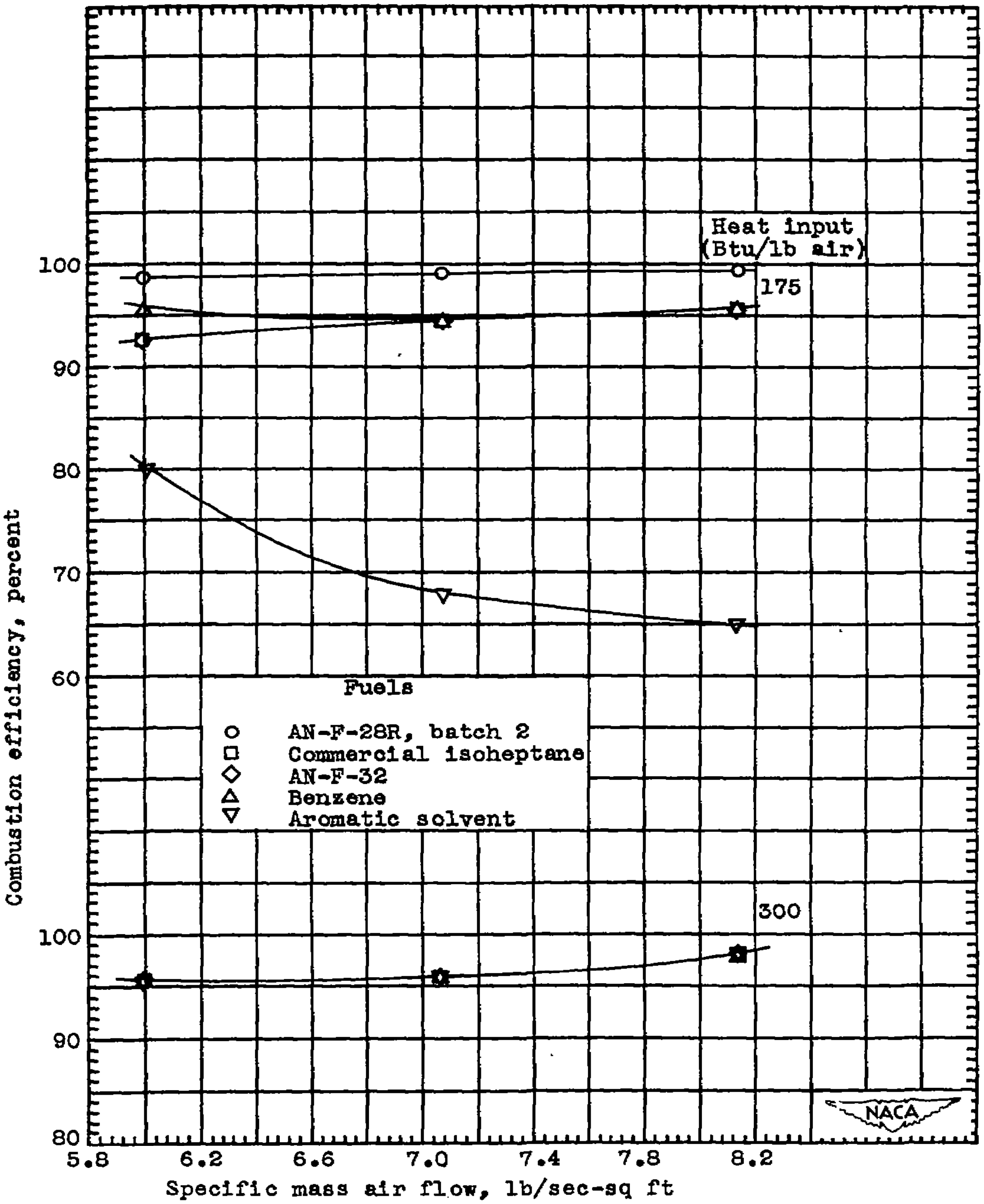


Figure 9. - Relation of combustion efficiency to mass air flow for several fuels at two values of heat input. Annular combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 51.1 inches mercury absolute; inlet-air total temperature, 250° F.

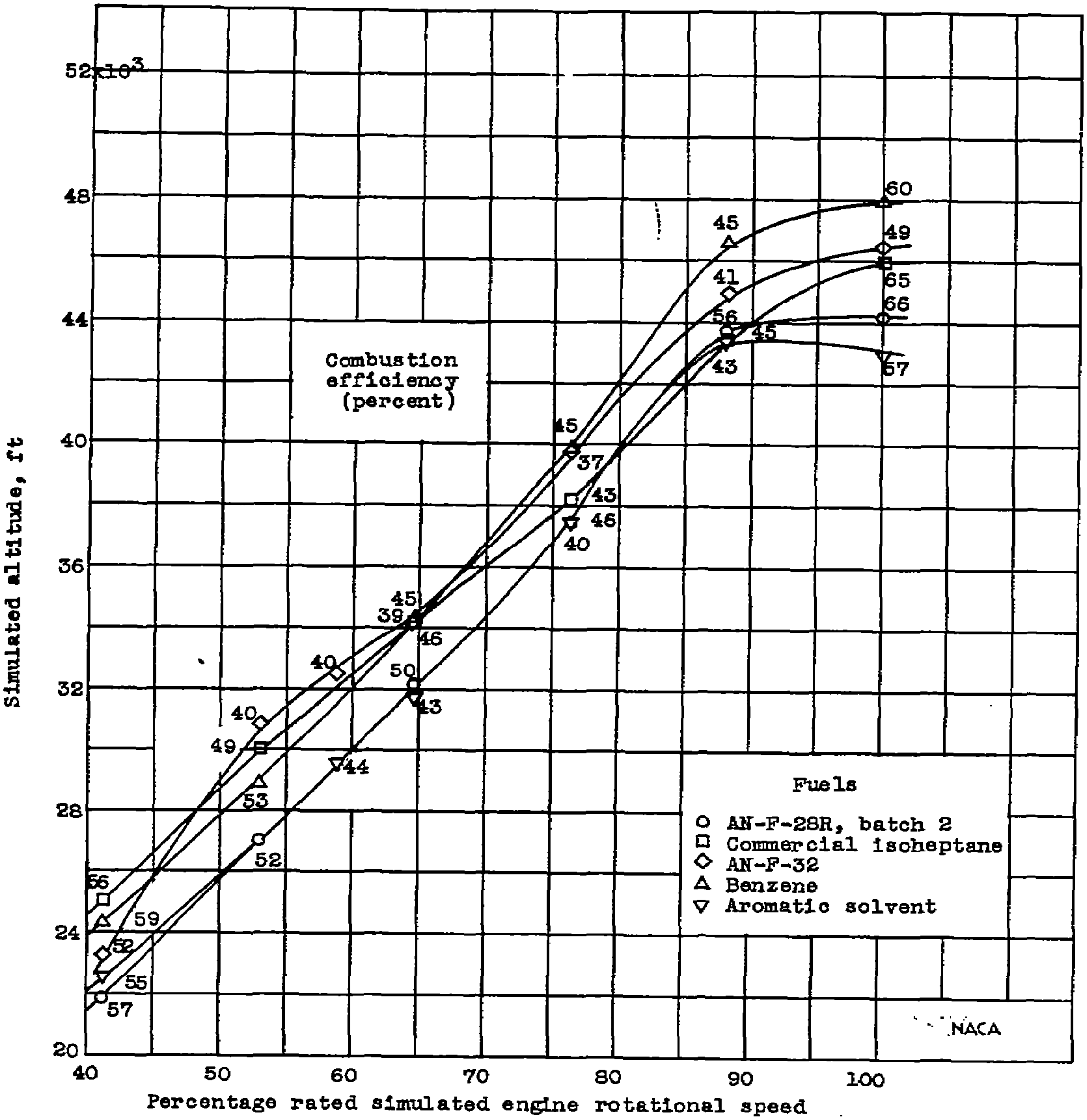


Figure 10. - Altitude operational limits as determined by various fuels in a $10\frac{3}{8}$-inch-diameter annular combustor. Inlet conditions varied with altitude and rotational speed.