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# RESEARCH MEMORANDUM

## PERFORMANCE OF A PAIR OF TUBULAR COMBUSTORS WITH AN EXTERNAL PILOT CHAMBER

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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## SUMMARY

The performance of a pair of tubular turbojet combustors interconnected by a 3-inch-inside-diameter ceramic-lined pilot chamber at the crossover tube position was investigated to determine the utility of the pilot chamber for improvement of high-altitude combustion efficiency, lean limits, and minimum engine speed. The pilot chamber was supplied with air from the combustor-inlet section and with sufficient fuel to maintain stoichiometric fuel-air ratios in the pilot chamber.

At pressures above 7.3 pounds per square inch absolute, the combustion efficiency of the combustors was not improved by the use of the pilot chamber except near the lean blow-out limit; at lower pressures, the combustion efficiency was slightly improved by the pilot chamber at all fuel-air ratios investigated. At windmilling conditions, the ignition limits of the combustors were increased several thousand feet by using the pilot chamber rather than a low-energy spark as an ignition source. The pilot chamber extended the lean limits of the combustors, permitting lower minimum engine rotational speeds below 45,000 feet altitude. Above that altitude the pilot chamber was ineffective, because combustion blow-out occurred at higher pressures in the pilot than in the main combustors.

The results of the investigation leave some doubt as to whether the pilot chamber offers sufficient performance improvements to justify the additional weight and complication of its installation on turbojet engines.

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## INTRODUCTION

External ceramic-lined pilot chambers for turbojet engines have been proposed as a means of improving altitude ignition and operating characteristics. A 3-inch-diameter ceramic-lined pilot chamber designed to fire directly into two adjacent tubular combustion chambers through ceramic-lined cross-over tubes was developed at the Battelle Memorial Institute (refs. 1 and 2). Stoichiometric fuel-air ratios were independently maintained in the pilot even at very low over-all combustor

[redacted]

fuel-air ratios. Niewoehner and Hazard (ref. 2) conducted an extensive investigation of the effect of such a pilot on the performance of two J47 combustors at a combustor-inlet pressure of 1 atmosphere. In addition, the performance of a pilot chamber operating alone in a closed-duct system was determined down to pressures as low as 3 pounds per square inch absolute. From the results obtained, it appeared likely that the pilot would act as a very stable zone of combustion for both reignition of the turbojet combustors after flame-out and maintenance of efficient combustion at the lean fuel-air ratios required for engine idling at 3361
higher altitudes.

While the previous investigations (refs. 1 and 2) indicated distinct potential advantages in combustor performance with the external piloting system, the investigations were limited to operating conditions above atmospheric pressures. The research described herein, which was conducted at the NACA Lewis laboratory, is an extension of the program to subatmospheric inlet pressures with tubular combustors to determine the magnitude of the indicated improvements cited in the earlier tests. Combustion performance was determined with the two tubular combustors operating alone, the pilot chamber operating alone, and both the pilot and the combustors operating together. Performance was evaluated in terms of

(1) Combustion efficiency and lean blow-out limits at a combustor reference velocity of 80 feet per second, an inlet temperature of 268° F, and a pressure range of 2.9 to 15 pounds per square inch absolute

(2) Ignition limits, which were determined for a combustor-inlet air temperature of 10° F and over a range of total air flows for the pilot and the two combustors from 0.75 to 3 pounds per second

(3) Altitude operating limits, which were determined at simulated engine rotational speeds above 2000 rpm

The pilot chamber and combustor test equipment used in this research were furnished by the Battelle Memorial Institute. Grateful acknowledgement is extended to R. W. Niewoehner of that laboratory for assistance in conducting the experimental program.

## APPARATUS

### Installation

A schematic diagram of the installation is shown in figure 1. Room-temperature combustion air or refrigerated air was drawn from the laboratory air-supply system, passed through the combustors, and discharged into the altitude exhaust system, permitting operation in the test section at pressures as low as 2.5 pounds per square inch absolute. Combustor-inlet temperatures were controlled by passing a portion of the inlet air through a heat exchanger located in a bypass line upstream of the test section. The heat exchanger was supplied with hot exhaust gases from a gasoline-fired slave combustor. The quantity of air flowing through the heat exchanger, the total air flow, and the combustion-chamber static pressure were regulated by remote-controlled valves with bypass-line valves for fine adjustment of flow and pressure. The two tubular combustors are from an axial-flow turbojet engine in the 90- to 100-pound-per-second air-flow class.



## Pilot Chamber

A view of the pilot-chamber installation with the pair of turbojet combustors is shown in figure 2. The pilot chamber was mounted on a section of a modified compressor rear-frame casting, and pilot air was taken from the combustor-inlet diffuser through a $\frac{5}{16}$ by $1\frac{1}{2}$-inch slot machined in the leading edge of the V-shaped divider between the combustor inlets. The air entered the pilot chamber through the mounting pad by which the pilot was bolted to the compressor rear frame. There was no provision for manual regulation of the air flow to the pilot chamber during this investigation.

A sketch of the pilot chamber is shown in figure 3. The pilot consisted of (1) a 4-inch-outside-diameter stainless-steel shell with a 1/2-inch-thick lining made of K-30 insulating firebrick and (2) an unlined air-entry section 3 inches in inside diameter. The two sections were connected by a V-band coupling to allow the pilot chamber to be disassembled easily for inspection and cleaning. The pilot fuel nozzles were mounted on a segment of a circular disk that blocked approximately 70 percent of the pilot inlet cross section and served as a flame stabilizer (fig. 3). Two fuel nozzles were used to simulate more closely the flow characteristics of the standard duplex fuel nozzles used in the J47 combustors. The two nozzles were swirl-type hollow-cone spray nozzles, rated at 1.35 and 8.30 gallons per hour (at a pressure differential of 100 lb/sq in.), inclined toward each other at an angle of $15^{\circ}$ to obtain even flame distribution at the two outlets of the pilot chamber. Two 2-inch-inside-diameter ceramic-lined exhaust tubes opened into the J47 combustors at the normal cross-over tube location. The cross-over tube openings in the combustor liners were enlarged to accommodate the pilot outlets.

## Fuel and Ignition Systems

The fuel system is shown diagrammatically in figure 4. The flows to the large and small slots of the combustor duplex nozzles and the large and small nozzles of the pilot chamber were regulated approximately in accordance with the pressure-flow schedule of the engine fuel flow divider. The larger openings in each case were used only when the pressure in the small openings exceeded 27 pounds per square inch. The total fuel flow and proportional flow to the large slots of the combustor and the large pilot nozzle were regulated by needle valves. MIL-F-5624A, grade JP-4, fuel was used throughout the investigation.

The spark ignition system consisted of a conventional spark plug connected to a 5000-volt, 60-cycle, 250-volt-ampere transformer. 3361

### Instrumentation

Combustors. - Total temperatures and pressures were measured at the three stations indicated in figure 1. The position of the instruments in each of the three planes is shown in figure 5. Combustor-inlet total temperatures and pressures were measured with four bare-junction unshielded iron-constantan thermocouples and nine total-pressure tubes at station 1 (fig. 5(a)). Combustor-outlet total temperatures and pressures were measured with 30 bare-junction unshielded chromel-alumel thermocouples at station 2 (fig. 5(b)) and 18 total-pressure tubes at station 3 (fig. 5(c)). All instruments were located at approximate centers of equal areas. Static-pressure orifices were installed at the walls as shown in figures 5(a) and (c).

The thermocouples were connected to self-balancing indicating potentiometers. The total-pressure probes and wall static-pressure taps were connected to common well manometers. A mercury manometer was used for measuring the gage static pressures. Total fuel flow and fuel flow to the pilot were measured by calibrated rotameters, and air flow was metered through concentric-hole, sharp-edged orifices.

Pilot chamber. - An estimate of the air flow through the pilot chamber was obtained with a calibrated pitot tube installed in the pilot chamber as shown in figure 3. Measurements of the dynamic and static pressures were obtained with an inclined U-tube manometer and an atmospheric reference manometer. A bare-junction chromel-alumel thermocouple imbedded in the ceramic lining of the pilot chamber with the tip almost exposed to the flame zone served to indicate flame-outs in the pilot chamber.

## PROCEDURE

### Combustion Efficiency and Lean Blow-Out

Comparison of the combustion efficiency and lean blow-out limits of the tubular combustors with and without the pilot chamber in operation was made at inlet-air static pressures of 2.9, 3.9, 7.3, and 14.7 pounds per square inch absolute, an inlet-air temperature of 268° F, and a reference velocity of 80 feet per second. The reference velocity is based on the maximum cross-sectional area of the combustor (0.48 sq ft) and the density of the inlet air. It was necessary to disassemble the pilot chamber after each series of tests to remove the carbon deposits formed by fuel cracking in the small nozzle passages. This condition could probably be corrected by proper design changes.

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Combustion efficiency was computed as the percentage ratio of actual to theoretical increase in enthalpy from combustor-inlet to -outlet instrumentation planes by using the methods of reference 3. The arithmetic mean of the 30 outlet thermocouple readings was used to obtain the value of combustor-outlet enthalpy.

## Ignition

Throughout the investigation, the pilot fuel flow was adjusted to maintain an approximately stoichiometric fuel-air ratio within the pilot chamber, since there was no manual control of the pilot air flow. The pilot chamber had no spark plug; thus, on light-off, the pilot-chamber outlets served the purpose of cross-ignition tubes, igniting the pilot-chamber gases from the flame in either combustor. Ignition and blow-out in the pilot chamber were detected by a change in the reading of the single thermocouple imbedded in the ceramic lining. For ignition tests, where the pilot flame was used as a source of ignition, the combustors were lighted momentarily in order to start the pilot. The combustor fuel flow was then shut off while the pilot remained lighted for the subsequent reignition tests of the two combustors. Ignition tests were made at a constant combustor-inlet temperature of approximately 10° F and total air flows of 0.75, 1.5, and 3.0 pounds per second (total air flow included flow through the pilot and both combustion chambers). The minimum combustor-inlet pressures at which the combustors would light, at any fuel-air ratio, were determined with the pilot as an ignition source and with a low-energy spark in each combustor as an ignition source.

## Altitude Operating Limits

The altitude operating limits of the combustors with and without the use of the pilot were determined over a range of engine speeds from 25 to 85 percent of maximum rated speed in the following manner: At a given simulated condition of altitude and engine speed, all inlet-air conditions were held constant and the fuel flow was increased until either the required temperature rise was attained, the combustor-outlet temperature decreased with further increase in fuel flow, or combustion blow-out occurred. If the required temperature rise was attained, the point was considered in the operating region for the engine; if either of the other two occurrences was encountered, the point was considered in the nonoperating region for the engine. This procedure was repeated for enough engine operating points to determine the limiting altitude for engine operation at each engine speed for a simulated flight Mach number of 0.6.

## RESULTS

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Data on combustion efficiency, flame blow-out, ignition, and altitude operating limits obtained in the combustors with and without the pilot chamber in operation are presented in table I.

### Combustion Efficiency and Lean-Limit Blow-Out

The combustion efficiency of the combustors with and without the pilot chamber in use is shown as a function of over-all fuel-air ratio in figure 6. At 14.7 and 7.3 pounds per square inch (figs. 6(a) and (b)), combustion efficiency was improved by the use of the pilot only for lean over-all fuel-air ratios; at the two lowest pressures of 3.9 and 2.9 pounds per square inch (figs. 6(c) and (d)), combustion efficiency was improved at all fuel-air ratios. The lean fuel-air-ratio limits of operation were extended somewhat by the use of the pilot at all pressures investigated.

### Ignition Limits

A comparison of ignition limits obtained with electric-spark and pilot-chamber flame sources is presented in figure 7. The ignition limits are shown as functions of combustor-inlet total pressure and total air flow at a constant combustor-inlet total temperature of 10° F. At a total air flow of 3 pounds per second the combustors had an ignition pressure limit of 6.1 pounds per square inch absolute with the pilot chamber and 7.6 pounds per square inch absolute with the spark ignition system. The blow-out limits for the combustors operating without the pilot and for the pilot operating without combustors are shown in figure 7 by broken lines. For the combustor tests, the criterion of blow-out was the loss of flame in both combustors. It may be noted from figure 7 that, over most of the range of air flow investigated, the pressure at which blow-out occurs in the pilot alone is about 0.7 pound per square inch higher than that at which the combustors blow out.

A curve representing air flows and pressures in the combustors for engine windmilling conditions, approximately 2100 rpm (data from ref. 4), is also included in figure 7. Pressure altitudes at a flight Mach number of 0.6 are indicated along this line. The point of intersection of the combustor blow-out curve with this windmilling line is at a pressure altitude of about 47,000 feet. The point of intersection of the two ignition-limit curves with the windmilling line is at a pressure altitude of about 25,000 feet for the low-energy-spark system and about 33,000 feet for the pilot chamber.

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## Altitude Operating Limits

The altitude operating limits of the combustors with and without the pilot chamber in use are shown in figure 8. The pilot chamber extended the minimum engine rotational speed at an altitude of 20,000 feet from 2500 to less than 2000 rpm. The extension of minimum operating speeds by use of the pilot decreased with increasing altitude until, at 45,000 feet, the minimum speed was the same with or without the pilot. Pilot blow-outs above 45,000 feet are indicated by the broken line.

## DISCUSSION

Combustion efficiencies for an operating pressure of 14.7 pounds per square inch absolute from reference 2 were approximately duplicated at the Lewis laboratory. This comparison is shown in figure 9. Combustion efficiency would not be expected to be influenced by the use of the pilot at conditions of high fuel-air ratios where the pilot fuel flow is a small percentage of the total fuel flow. For very lean fuel-air ratios, however, where the pilot fuel flow would be a larger portion of the total fuel flow, the pilot should have a greater effect on the over-all efficiency. Thus, as expected, at combustor-inlet pressures above 7.3 pounds per square inch absolute, combustion efficiency was increased only near the lean limits of operation; at the lower inlet pressures, an increase in efficiency was noted at all fuel-air ratios (fig. 6). It would also be expected that the use of the pilot would extend the lean blow-out limit of the combustors to lower over-all fuel-air ratios, since the pilot passes a very small percentage of the total air flow and burns it at stoichiometric fuel-air ratios. Unstable operation of the pilot, noted particularly at combustor-inlet pressures of 3.9 and 7.3 pounds per square inch absolute, however, may account for the fact that the pilot did not extend the lean limit of operation appreciably at these conditions.

The pilot chamber increased the ignition limits of the combustors several thousand feet over those of a low-energy spark source at engine windmilling speeds. The maximum altitude at which the combustors can be ignited at windmilling speeds by any source of ignition is about 47,000 feet, since the combustor blow-out line intercepts the windmilling curve at this altitude (fig. 7).

The pilot chamber in its present configuration had blow-out limits approximately 0.7 pound per square inch higher than the combustors over the range of air flows investigated. These pilot blow-out limits are in fair agreement with data presented in reference 2, as shown in figure 10. At low altitudes, where the pilot is not pressure-limited, the stoichiometric pilot fuel-air mixture produces sufficient temperature rise, even without the combustors in operation, to satisfy the low-engine-speed temperature-rise requirements. The minimum engine rotational speeds are therefore extended, as noted in figure 8. At high altitudes (above 45,000 ft in fig. 8), the pilot chamber can no longer extend the minimum engine speed because of the relatively high pressure blow-out limit of the pilot with respect to the engine combustors.

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The installation of a piloting device such as the one discussed herein on a turbojet engine has several inherent disadvantages, such as added weight, mechanical complication, and maintenance. The pilot chamber must therefore effect marked combustor improvements to warrant its installation. The results of this investigation indicate that the combustion efficiency, lean limit, and altitude engine operating limit of the combustors were not greatly improved with the use of the pilot chamber. The ignition limits at engine windmilling speeds, however, were increased eight thousand feet.

It is not within the scope of this report to determine whether or not the combustor performance improvements shown by the use of the pilot chamber are large enough to warrant pilot-chamber installations on these engines. It is likely, however, that, for an equal expenditure of effort, turbojet combustors could be designed to operate at high altitudes equally well with less additional weight and mechanical complication.

## SUMMARY OF RESULTS

The results of an investigation of the low-pressure performance of a pair of tubular combustors equipped with an external pilot chamber are as follows:

1. The over-all combustion efficiency of the system was not increased by the use of the pilot chamber at combustor-inlet pressures above 7.3 pounds per square inch absolute except near the lean blow-out limits. The combustion efficiency was increased at all fuel-air ratios investigated at pressures below 7.3 pounds per square inch absolute.

2. The blow-out pressure limit was about 0.7 pound per square inch higher for the pilot chamber than for the combustors; thus, the altitude combustion limit for the pilot was lower than that of the combustors.

3. Pilot-chamber operation extended the lean limit of the combustors; consequently, the minimum engine speed was extended by the use of the pilot chamber at altitudes below 45,000 feet, where the pilot chamber was not pressure-limited.

4. For engine windmilling speeds, the ignition limits of the combustors were improved by several thousand feet by using the pilot chamber rather than a low-energy spark as an ignition source.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 7, 1954

## REFERENCES

1. Hazard, H. R.: Use of Ceramics in Gas-Turbine Combustion Systems. Battelle Memorial Inst., Columbus (Ohio), Sept. 15, 1951. (Contract AF 33(038)-841.)

2. Niewoehner, R. W., and Hazard, H. R.: First Technical Report on Experimental Evaluation of a Ceramic Pilot Chamber for Turbojet Engines. Battelle Memorial Inst., Columbus (Ohio), Aug. 1, 1953. (Contract AF 33(038)-841.)

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3. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

4. Wallner, Lewis E., and Welna, Henry J.: Generalization of Turbojet and Turbine-Propeller Engine Performance in Windmilling Condition. NACA RM E51J23, 1951.

TABLE I. - EXPERIMENTAL DATA

(a) Over-all combustion efficiency with pilot burning.

| Run | Combustor-inlet pressure, lb/sq in. abs | Estimated pilot air flow, lb/sec | Total air flow, lb/sec | Combustor reference velocity, ft/sec | Over-all fuel-air ratio | Combustion efficiency, percent | Combustor-inlet temperature, °F | Combustor-outlet average temperature, °F |
|---|---|---|---|---|---|---|---|---|
| 1 | 14.7 | 0.07 | 4.2 | 79 | 0.0188 | 88.3 | 264 | 1410 |
| 2 | | | | | .0130 | 90.8 | 267 | 1110 |
| 3 | | | | | .0097 | 92.4 | 268 | 920 |
| 4 | | | | | .0077 | 93.9 | 270 | 800 |
| 5 | | | | | .0052 | 88.3 | 271 | 615 |
| 6 | | | | | .0028 | 90.3 | 267 | 465 |
| [a]7 | | | | | .00076 | ---- | 268 | 335 |
| 8 | 7.25 | 0.033 | 2.10 | 79 | 0.0206 | 85.7 | 266 | 1470 |
| 9 | | | | | .0160 | 88.5 | 270 | 1260 |
| 10 | | | | | .0126 | 95.0 | 268 | 1120 |
| 11 | | | | | .0091 | 87.3 | 270 | 850 |
| [b]12 | | | | | .0061 | 97.6 | 269 | 710 |
| [a]13 | | | | | .0011 | ---- | 268 | 460 |
| 14 | 3.93 | 0.025 | 1.14 | 80 | 0.0219 | 82.8 | 268 | 1500 |
| 15 | | | 1.15 | 81 | .0187 | 85.8 | 270 | 1310 |
| 16 | | | 1.14 | 80 | .0149 | 73.7 | 269 | 1050 |
| [c,d]17 | | | 1.12 | 79 | .0097 | 74.9 | 270 | 800 |
| 18 | 2.93 | 0.018 | 0.86 | 81 | 0.0262 | 71.6 | 261 | 1520 |
| 19 | | | .86 | 81 | .0169 | 77.6 | 261 | 1180 |
| 20 | | | .87 | 82 | .0148 | 65.1 | 260 | 950 |
| [e,f]21 | | | .85 | 80 | .0117 | 30.9 | 260 | 525 |
| [e,f]22 | | | .85 | 80 | .0127 | 37.8 | 260 | 610 |
| [e,f]23 | | | .86 | 83 | .0104 | 37.9 | 277 | 560 |

[a]Pilot burning only.
[b]Incipient blow-out of combustors.
[c]Complete blow-out of combustors.
[d]Blow-out of pilot.
[e]Blow-out of one combustor only.
[f]Pilot operation unstable.

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TABLE I. - Continued. EXPERIMENTAL DATA

(b) Over-all combustion efficiency without pilot burning.

| Run | Combustor-inlet pressure, lb/sq in. abs | Estimated pilot air flow, lb/sec | Total air flow, lb/sec | Combustor reference velocity, ft/sec | Over-all fuel-air ratio | Combustion efficiency, percent | Combustor-inlet temperature, °F | Combustor-outlet average temperature, °F |
|---|---|---|---|---|---|---|---|---|
| 24 | 14.7 | 0.07 | 4.20 | 81 | 0.0202 | 87.6 | 290 | 1500 |
| 25 | | | 4.18 | 78 | .0162 | 90.4 | 267 | 1290 |
| 26 | | | 4.17 | 78 | .0128 | 92.0 | 266 | 1105 |
| 27 | | | 4.20 | 79 | .0092 | 94.9 | 274 | 910 |
| 28 | | | 4.20 | 78 | .0063 | 96.6 | 265 | 715 |
| 29 | | | 4.16 | 78 | .0037 | 80.0 | 271 | 500 |
| [b]30 | | | 4.18 | 78 | .0024 | 72.6 | 268 | 400 |
| 31 | 7.25 | 0.033 | 2.11 | 80 | 0.0206 | 85.8 | 268 | 1475 |
| 32 | | | 2.11 | 80 | .0160 | 90.2 | 270 | 1280 |
| 33 | | | 2.10 | 80 | .0124 | 91.1 | 268 | 1080 |
| 34 | | | 2.10 | 80 | .0093 | 86.1 | 268 | 850 |
| 35 | | | 2.10 | 80 | .0061 | 80.2 | 267 | 630 |
| [e]36 | | | 2.10 | 80 | .0050 | 74.7 | 267 | 550 |
| 37 | 3.93 | 0.025 | 1.14 | 80 | 0.0227 | 76.6 | 272 | 1455 |
| 38 | | | 1.12 | 79 | .0198 | 76.7 | 275 | 1325 |
| 39 | | | 1.10 | 77 | .0157 | 74.7 | 270 | 1100 |
| [e]40 | | | 1.125 | 79 | .0111 | 48.0 | 270 | 660 |
| 41 | 2.93 | 0.018 | 0.835 | 79 | 0.0263 | 72.0 | 265 | 1535 |
| 42 | | | .855 | 80 | .0215 | 67.3 | 261 | 1260 |
| 43 | | | .865 | 81 | .0164 | 67.9 | 261 | 1050 |
| [b]44 | | | .850 | 80 | .0137 | 59.4 | 261 | 850 |

[b]Incipient blow-out of combustors.
[e]Blow-out of one combustor only.

TABLE I. - Continued. EXPERIMENTAL DATA

(c) Combustor and pilot blow-out.[g]

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| Run | Combustor-inlet pressure, lb/sq in. abs | Total air flow, lb/sec | Combustor reference velocity, ft/sec | Combustor-inlet temperature, °F |
|---|---|---|---|---|
| Combustor blow-out | | | | |
| 45 | 4.73 | 3.0 | 111 | 2 |
| 46 | 4.95 | ↓ | 108 | 11 |
| 47 | 4.93 | ↓ | 108 | 11 |
| 48 | 4.58 | ↓ | 116 | 10 |
| 49 | 5.23 | ↓ | 102 | 10 |
| 50 | 4.68 | ↓ | 114 | 9 |
| 51 | 2.88 | 1.5 | 93 | 13 |
| 52 | 2.93 | ↓ | 91 | 10 |
| 53 | 2.88 | ↓ | 92 | 9 |
| 54 | 2.38 | .75 | 57 | 16 |
| 55 | 2.68 | ↓ | 50 | 11 |
| 56 | 2.38 | ↓ | 56 | 13 |
| Pilot blow-out | | | | |
| 57 | 5.64 | 3.0 | 94 | 8 |
| 58 | 5.90 | 3.0 | 90 | 7 |
| 59 | 3.53 | 1.5 | 75 | 11 |
| 60 | 3.68 | 1.5 | 73 | 12 |
| 61 | 2.80 | .75 | 48 | 15 |
| 62 | 2.62 | .75 | 51 | 16 |

[g]Points recorded at blow-out.

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TABLE I. - Continued. EXPERIMENTAL DATA

(d) Spark and pilot ignition.

| Run | Combustor-inlet pressure, lb/sq in. abs | Total air flow, lb/sec | Combustor reference velocity, ft/sec | Combustor-inlet temperature, °F | Ignition |
|---|---|---|---|---|---|
| Spark ignition | | | | | |
| 63 | 3.27 | 0.75 | 41 | 13 | Yes |
| 64 | 2.78 | ↓ | 48 | 14 | No |
| 65 | 3.05 | ↓ | 44 | 13 | ↓ |
| 66 | 3.76 | 1.5 | 70 | 8 | ↓ |
| 67 | 4.25 | ↓ | 62 | 8 | ↓ |
| 68 | 5.49 | ↓ | 48 | 7 | Yes |
| 69 | 4.98 | ↓ | 53 | 6 | ↓ |
| 70 | 4.62 | ↓ | 57 | 7 | ↓ |
| 71 | 6.95 | 3.0 | 75 | 0 | No |
| 72 | 7.68 | ↓ | 68 | 2 | Yes |
| 73 | 7.98 | ↓ | 66 | 3 | Yes |
| Pilot ignition | | | | | |
| 74 | 2.94 | 0.75 | 46 | 16 | Yes |
| 75 | 2.98 | ↓ | 46 | 20 | No |
| 76 | 3.20 | ↓ | 42 | 20 | Yes |
| 77 | 4.17 | 1.5 | 63 | 17 | ↓ |
| 78 | 7.35 | 3.0 | 72 | 9 | ↓ |
| 79 | 6.85 | ↓ | 78 | 9 | ↓ |
| 80 | 6.12 | ↓ | 87 | 9 | No |

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TABLE I. - Concluded. EXPERIMENTAL DATA

(e) Altitude operating limits with and without pilot burning.

| Run | Combustor-inlet pressure, lb/sq in. abs | Total air flow, lb/sec | Combustor-inlet temperature, °F | Simulated flight altitude, ft | Simulated engine speed, rpm |
|---|---|---|---|---|---|
| With pilot burning | | | | | |
| [c,d]81 | 3.81 | 1.66 | --- | 40,000 | 2500 |
| [c,d]82 | 3.03 | 1.55 | 40 | 50,000 | 3500 |
| [c,d]83 | 4.40 | 2.02 | 18 | 40,000 | 3000 |
| [c,d]84 | 4.64 | 2.02 | 15 | 40,000 | 3000 |
| [b]85 | 9.05 | 3.6 | 66 | 20,000 | 2500 |
| [a,c]86 | 8.36 | 3.0 | 68 | 20,000 | 2000 |
| Without pilot burning | | | | | |
| [c]87 | 3.43 | 1.4 | -26 | 40,000 | 2000 |
| [c]88 | 3.86 | 1.64 | -3 | ↓ | 2500 |
| [b]89 | 4.40 | 2.0 | 14 | ↓ | 3000 |
| [h]90 | 5.12 | 2.4 | 34 | ↓ | 3500 |
| [h]91 | 3.86 | 1.9 | 75 | 50,000 | 4000 |
| [b]92 | 3.22 | 1.54 | 48 | 55,000 | 4000 |
| [h]93 | 4.45 | 1.8 | 207 | 65,000 | 6000 |
| [b]94 | 3.03 | 1.16 | 212 | 75,000 | 6000 |

[a]Pilot burning only.
[b]Incipient blow-out of combustors.
[c]Complete blow-out of combustors.
[d]Blow-out of pilot.
[h]Operable point.

[redacted]

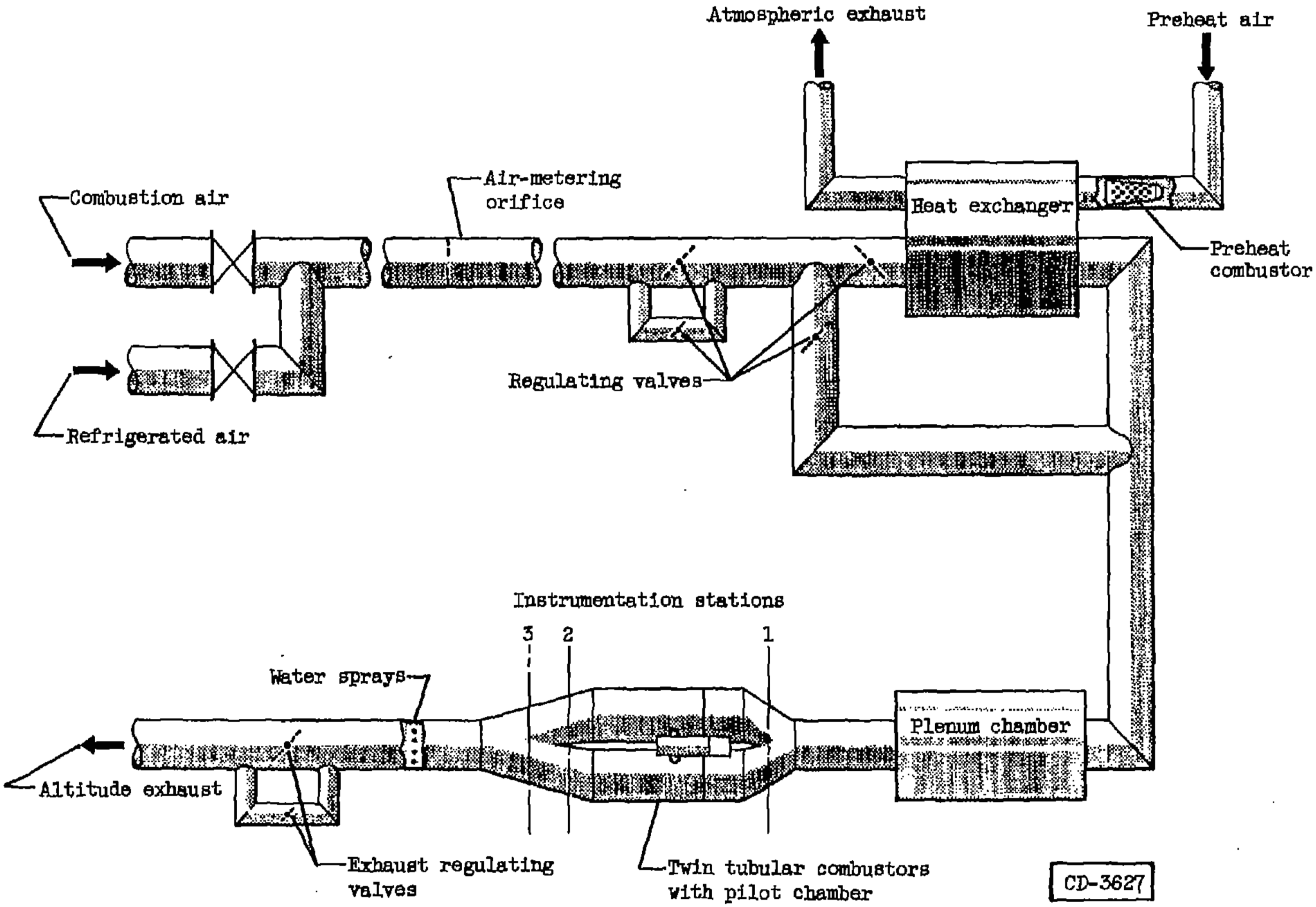



Figure 1. - Installation of combustors and pilot.

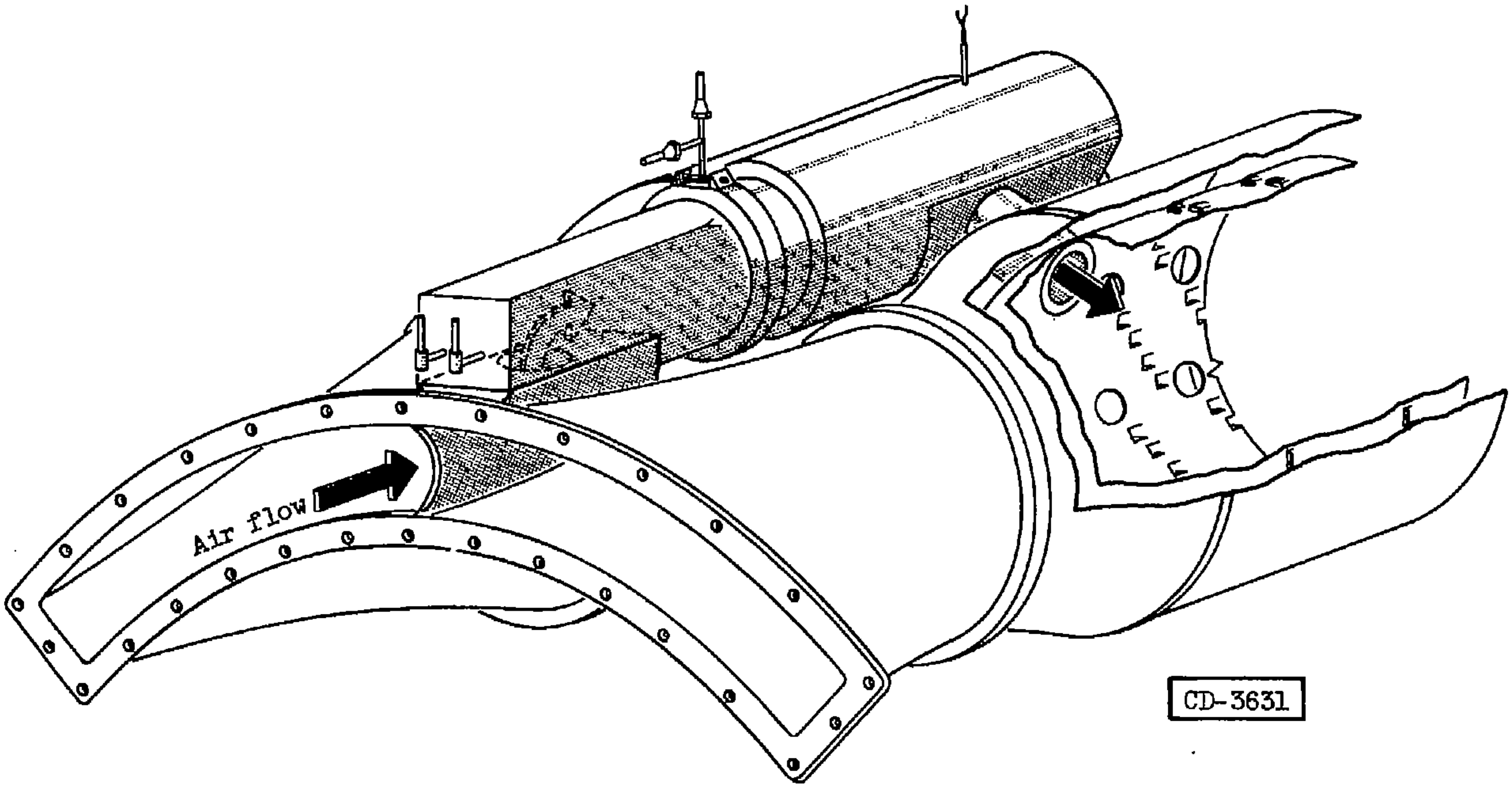



Figure 2. - Three-quarter view of pilot installation on pair of tubular combustors.

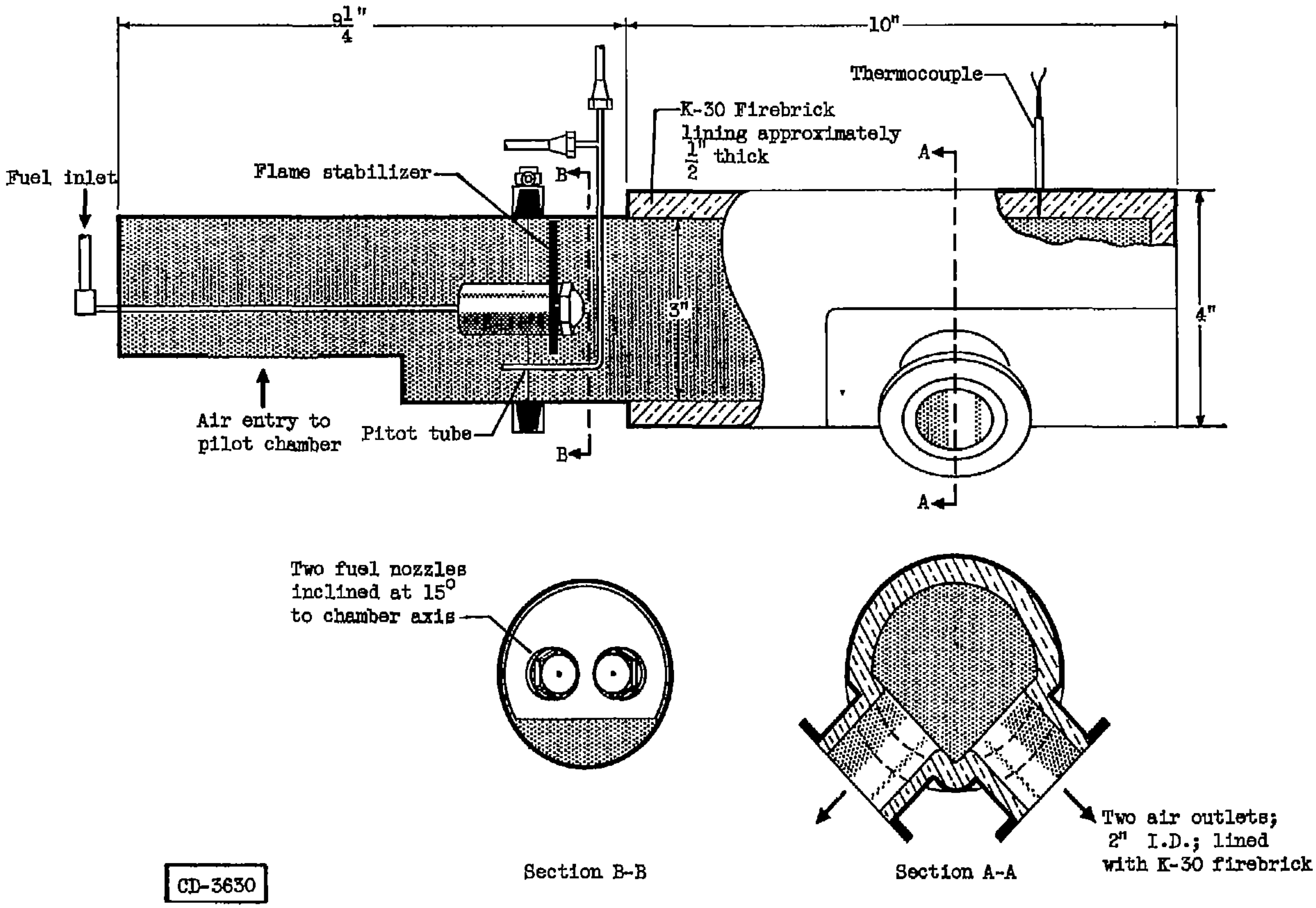



Figure 3. - Sketch of ceramic-lined pilot chamber.

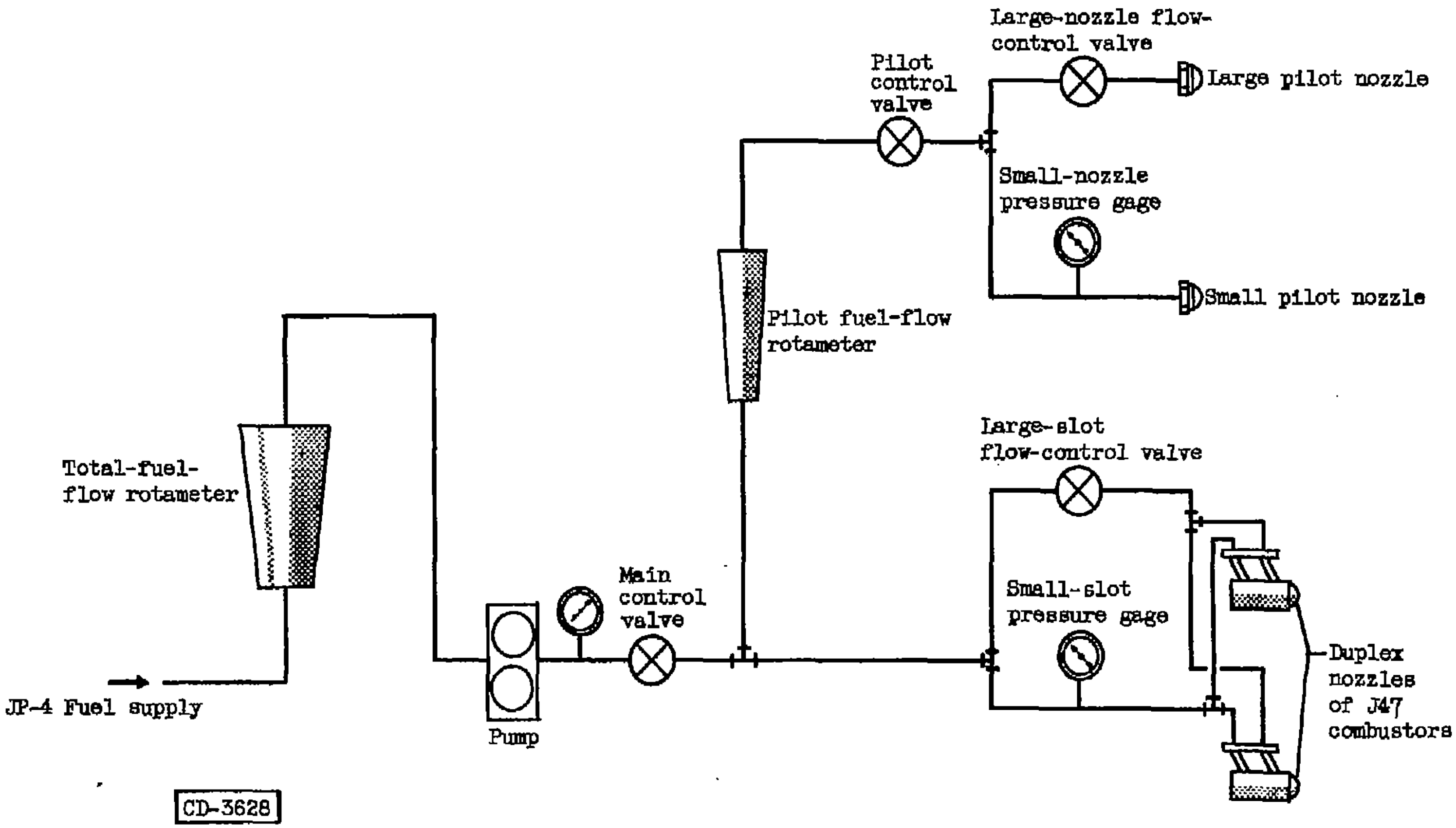
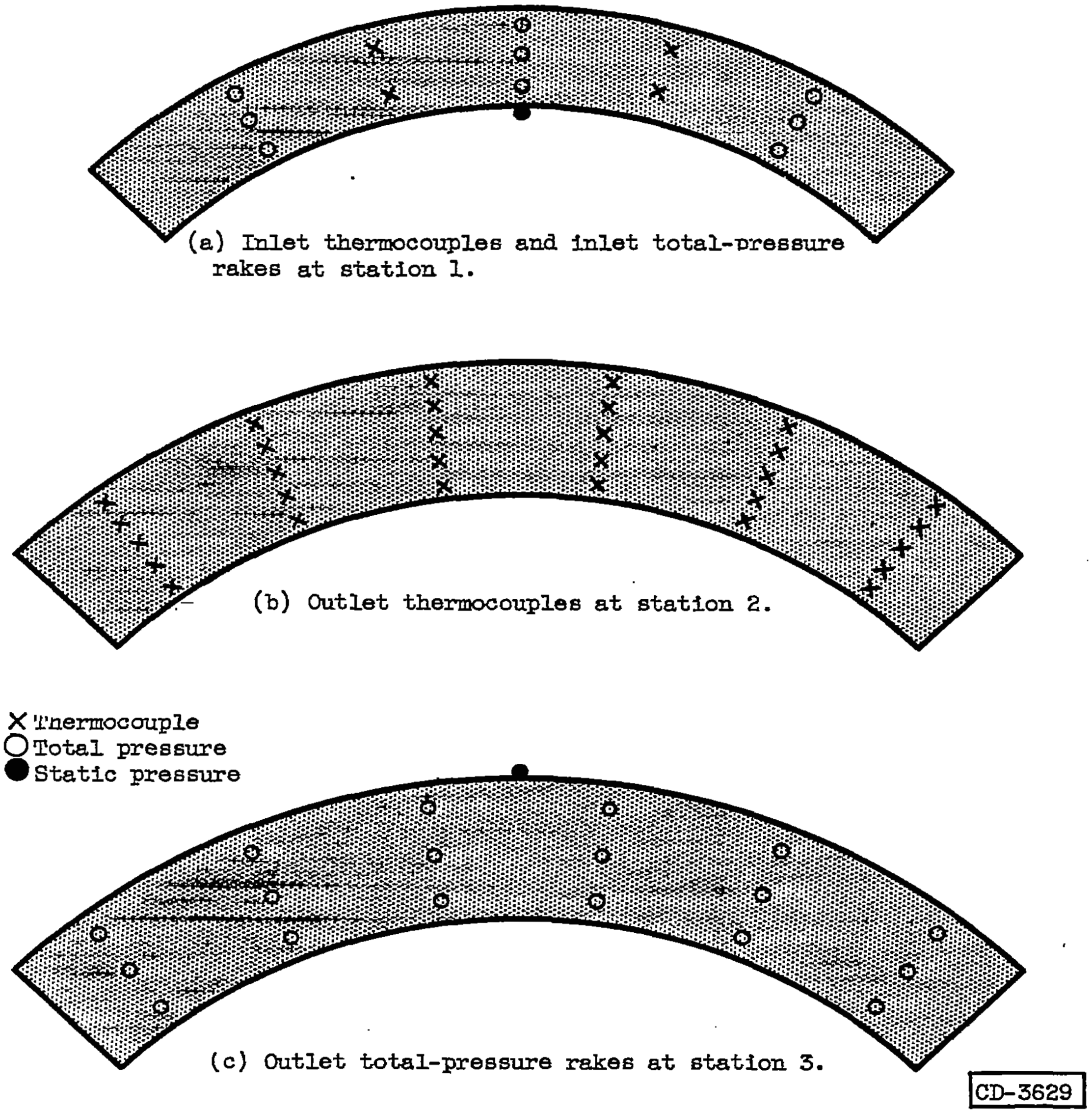



Figure 4. - Fuel system for pilot chamber and combustors.




(a) Inlet thermocouples and inlet total-pressure rakes at station 1.

(b) Outlet thermocouples at station 2.

(c) Outlet total-pressure rakes at station 3.

Figure 5. - Instrumentation.

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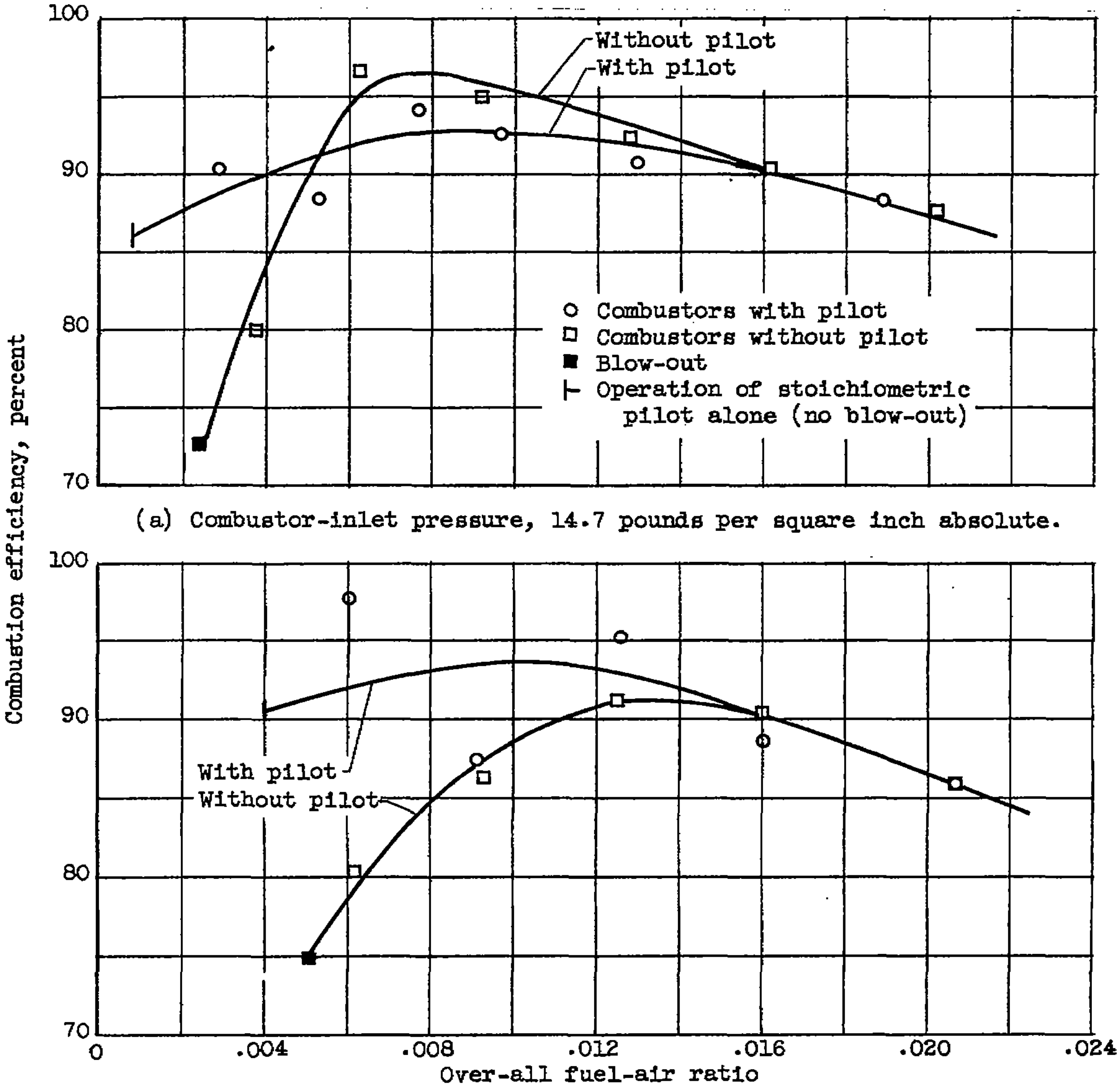


(a) Combustor-inlet pressure, 14.7 pounds per square inch absolute.

(b) Combustor-inlet pressure, 7.3 pounds per square inch absolute.

Figure 6. - Combustion efficiency of pair of tubular combustors with and without pilot chamber in operation. Operating conditions: inlet temperature, 268° F; combustor reference velocity, 80 feet per second.

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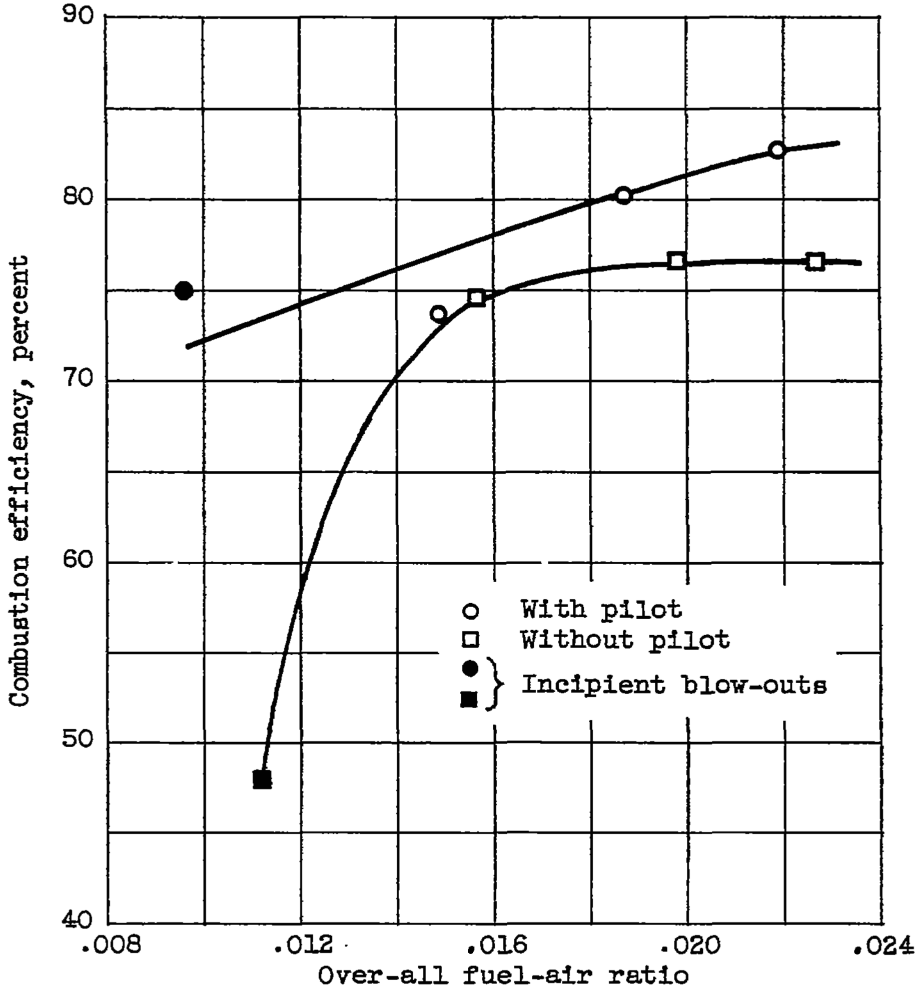


(c) Combustor-inlet pressure, 3.9 pounds per square inch absolute.

Figure 6. - Continued. Combustion efficiency of pair of tubular combustors with and without pilot chamber in operation. Operating conditions: inlet temperature, 268° F; combustor reference velocity, 80 feet per second.

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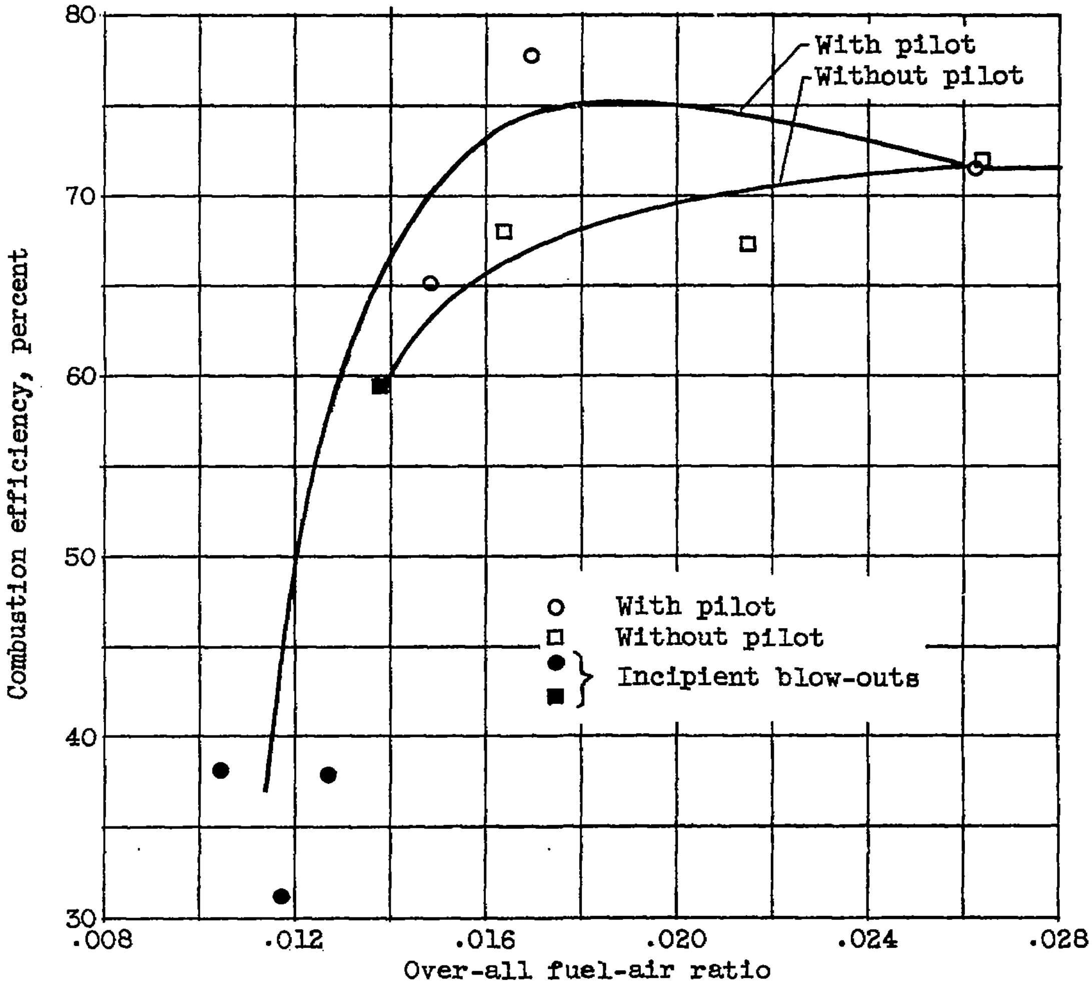


(d) Combustor-inlet pressure, 2.9 pounds per square inch absolute.

Figure 6. - Concluded. Combustion efficiency of pair of tubular combustors with and without pilot chamber in operation. Operating conditions: inlet temperature, 268° F; combustor reference velocity, 80 feet per second.

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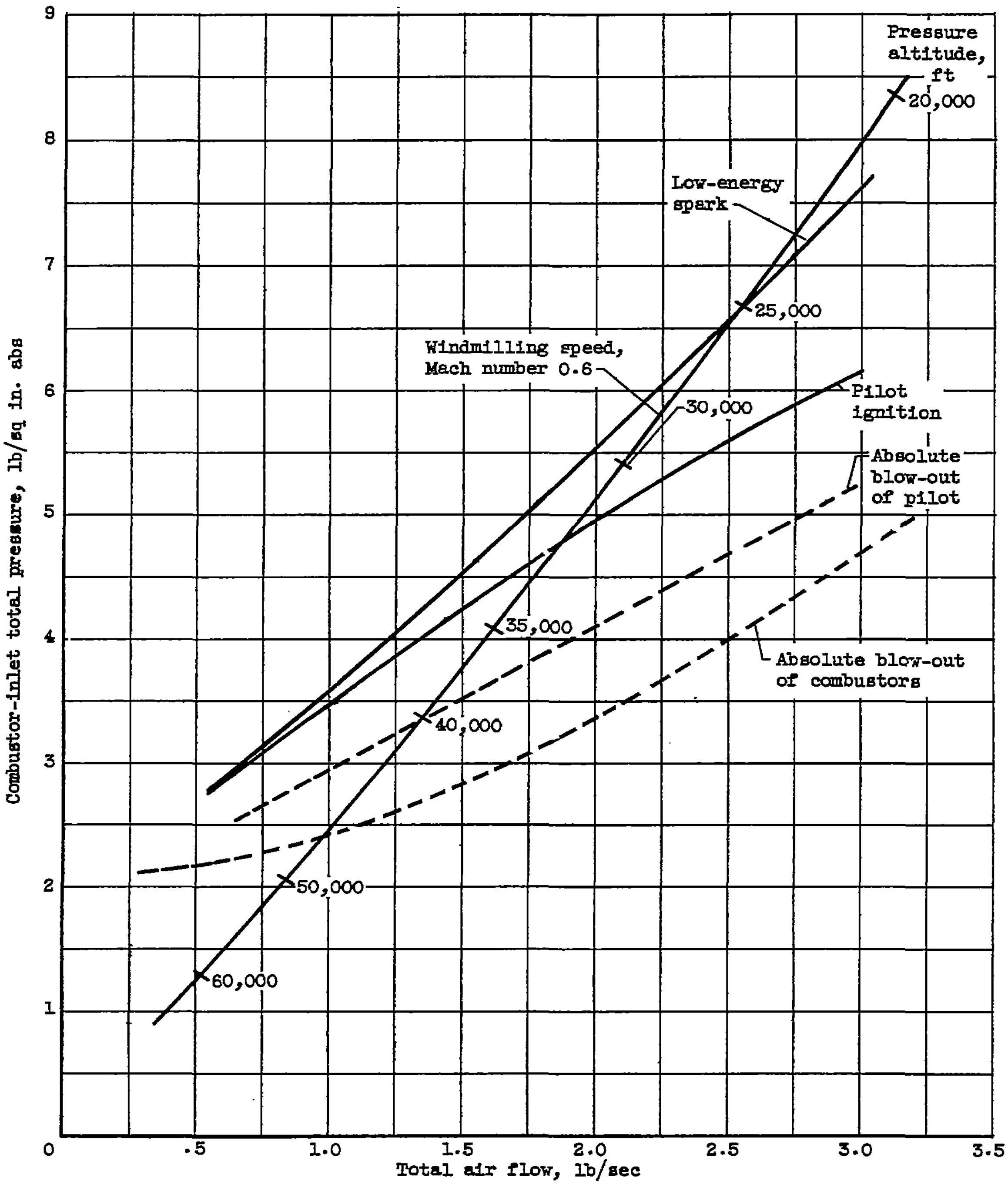


Fig. 7. - Ignition limits of pair of tubular combustors showing absolute-pressure blow-out limits of combustors and pilot. Inlet temperature, 10° F.

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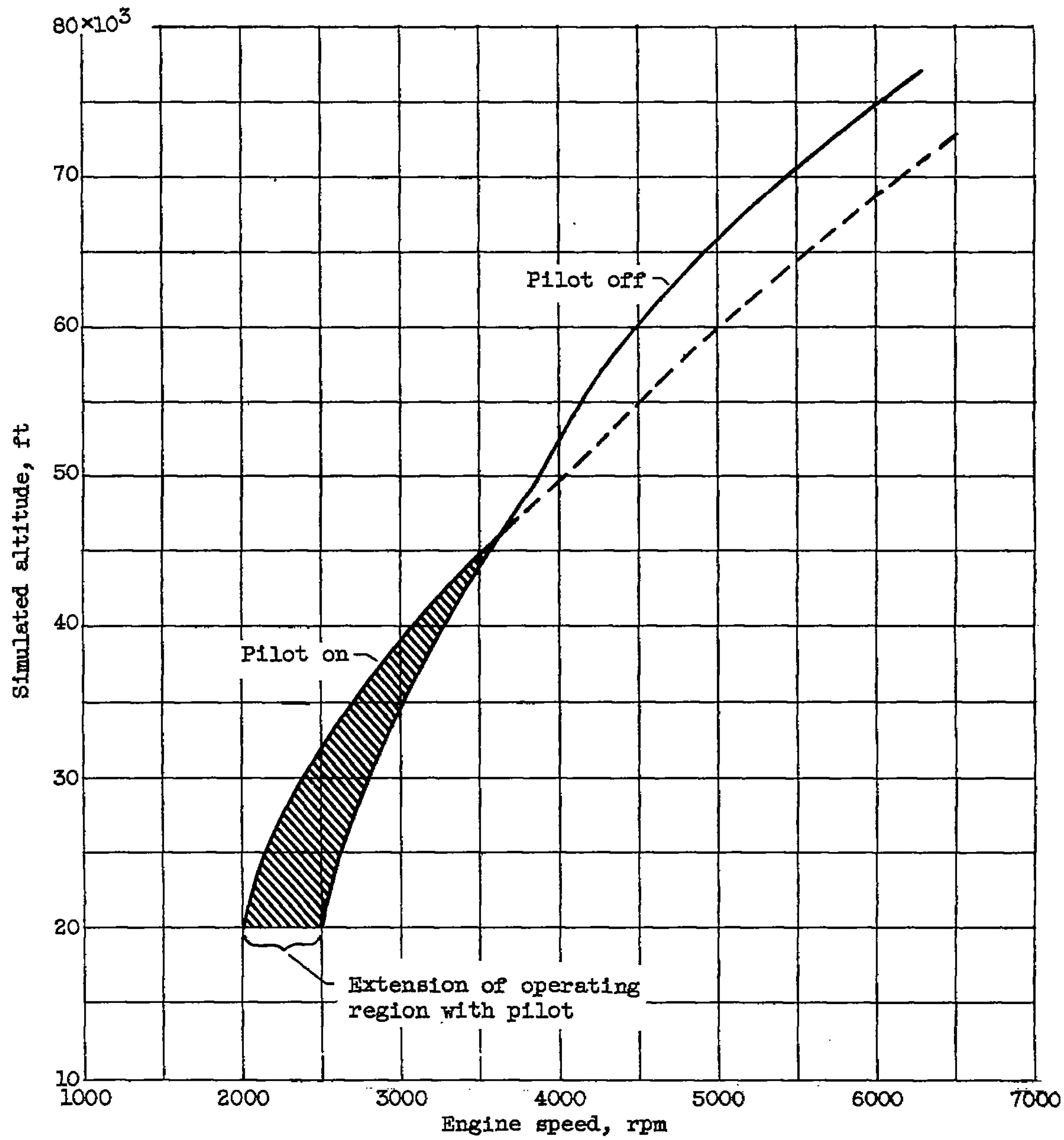


Figure 8. - Altitude operating limits of pair of tubular combustors with and without pilot chamber in operation. Simulated flight Mach number, 0.6.

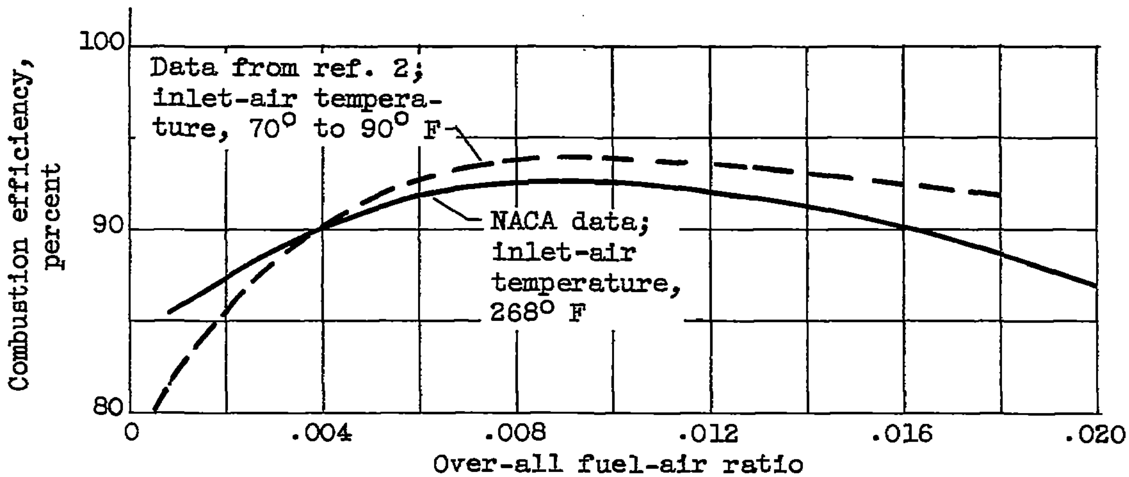


Figure 9. - Comparison of combustion efficiency of pair of tubular combustors with pilot chamber in operation with data from reference 2. Operating conditions: inlet pressure, 14.7 pounds per square inch absolute; combustor reference velocity, 80 feet per second.

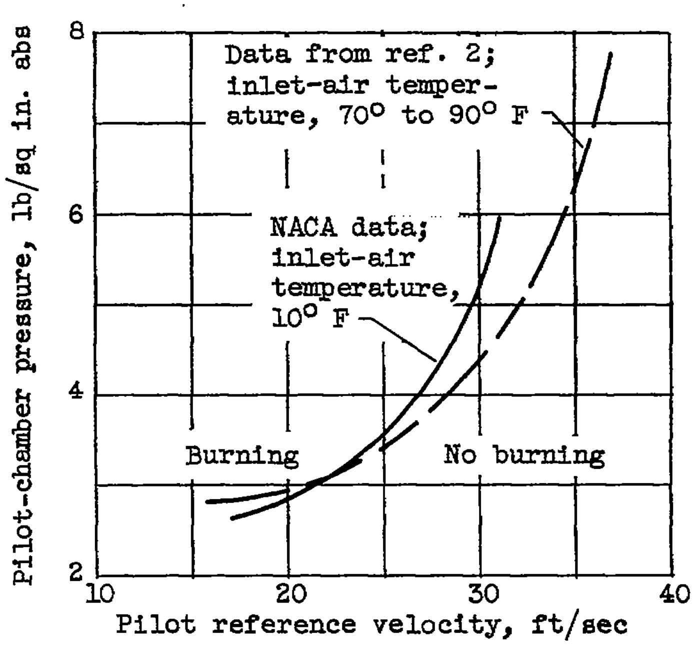


Figure 10. - Comparison of absolute blow-out limits of pilot chamber operating at stoichiometric fuel-air ratios with data of reference 2.

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