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EFFECT OF IMMERSED SURFACES IN COMBUSTION ZONE ON EFFICIENCY AND STABILITY OF 5-INCH-DIAMETER RAM-JET COMBUSTOR

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NATIONAL ADVISORY COMMITTEE
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EFFECT OF IMMERSED SURFACES IN COMBUSTION ZONE ON EFFICIENCY AND STABILITY OF 5-INCH-DIAMETER RAM-JET COMBUSTOR

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SUMMARY

An extension of previous work on immersed surfaces in the combustion zone of a ram-jet engine is reported. It is shown that when a single blade is mounted perpendicular to and downstream of a V-gutter flame holder in a 5-inch-diameter ram jet, the performance of the ram jet is markedly affected by the axial position of the blade. At an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0, it is possible to increase the combustion efficiency of the ram jet from 60 percent to 80 percent by proper location of the blade. However, the stability of the system without auxiliary piloting is poorer with the blade present. The higher combustion efficiency is obtained with considerably less pressure drop than was encountered in a previous investigation with a multiple-blade arrangement that gave high efficiencies. A small amount of continuous pilot heat can effect large improvements in stability limits.

INTRODUCTION

One of the basic advantages attributed to the ram-jet combustor is its mechanical simplicity. However, a certain amount of hardware must be incorporated in the combustor in order to stabilize a flame and have it propagate through the high-velocity combustible mixtures flowing through the ram jet.

The basic types of flame holders currently found to be suitable are the can and simple baffle, such as the V-gutter. The can flame holder provides a greater control of the combustion progress through the engine, but usually has a larger pressure drop and more complicated construction than the simple baffle-type flame holders. The baffle flame holder, while permitting a comparable stability regime with less pressure drop, maintains essentially no control over the subsequent mixing and flame-spreading process beyond its normal wake region.

The use of flame-immersed surfaces offers a means of retaining the mechanical simplicity and low pressure losses of the gutter flame-holder system while achieving some measure of control of the mixing in the combustion zone. Reducing the pressure losses of the combustor with flame-immersed surfaces below those of reference 1 would be particularly advantageous in an afterburner application, for example, since the additional drag accompanying the added immersed surface during nonburning operation would be relatively small.

It was shown in reference 1 that the introduction of immersed surfaces in the combustion zone downstream of a single V-gutter flame holder improved both the combustion efficiency and stability over those obtained with the gutter alone. The improvement in efficiency was obtained through increased mixing of hot combustion products with incoming combustible mixture, since the effects of temperature of the surfaces was of secondary importance. The blades used in the investigation of reference 1 were placed so that they would not interfere with the normal recirculation zone of the V-gutter. However, the increased efficiencies were obtained at the expense of somewhat larger pressure drops than those obtained with the gutter alone.

The present investigation was undertaken to determine the effect on combustion efficiency and stability of blades located within the immediate wake of a V-gutter flame holder and, if possible, to find some location and orientation of blades for optimum combustion efficiency and improved stability limits with a minimum of pressure loss.

The experimental work was performed with a 5-inch-diameter connected-pipe ram jet at the NACA Lewis laboratory.

APPARATUS

The connected-pipe setup used in this investigation is shown schematically in figure 1. Electrically preheated and metered air at 40 pounds per square inch gage pressure was supplied to the inlet of the tank containing the air-control unit. Air mass flow was controlled by maintaining choked flow through the air-control unit shown in the insert of figure 1 and exposing a sufficient number of holes in the sliding plates to obtain the desired mass flow. Fuel was introduced through an air-atomizing spray bar at the diffuser inlet.

The fuel-air mixture passed through the 10-foot-long diffuser, where sufficient time was available for vaporizing and mixing, and was ignited by a hydrogen-oxygen pilot flame located behind the flame holder. The flame holder was a $1\frac{1}{2}$- by $1\frac{1}{2}$-inch V-gutter extending across a diameter and blocking about 38 percent of the combustor cross-sectional area. The combustion chamber, a 5-inch-diameter water-cooled pipe section, was 36 inches long. Two different burner spool sections were used, as shown in figure 2(a) and (b). The blades, which were 13/16- by $3\frac{1}{2}$- by 1/8-inches, were made of molybdenum coated with molybdenum disilicide and were cantilever-mounted in the combustor through pipe fittings. The various configurations investigated are indicated in figure 2(c). The static-pressure drop was measured by a mercury manometer connected from the inlet pressure tap in the combustor wall upstream of the flame holder to the similar downstream tap at the exhaust end of the combustion chamber.

A variable-area exhaust nozzle controlled the burner-inlet pressure. In order to cool the combustion products to 1060° R and quench the reaction, water was introduced through two air-atomizing spray bars just downstream of the exhaust nozzle. The equilibrium exhaust-gas temperatures were measured by an array of thermocouples located about 15 feet farther downstream. The combustion efficiency was then calculated by an enthalpy balance.

PROCEDURE AND CALCULATION

The procedure used in obtaining the test data was as follows: The air mass flow and temperature were set at a predetermined value. The burner was ignited and the fuel flow set at some value in the stable burning regime. The pilot was turned off before recording data. The inlet pressure was then set at the desired operating point by adjusting the variable-area exhaust nozzle. The quench-water flow rate was set so that the exhaust-gas temperature was maintained at about 1060° R.

The combustion efficiency was then calculated by the following equation:

$$\eta = \frac{\Delta H_w + \Delta H_e + \Delta H_j}{(H_c)(f/a)} \qquad (1)$$

where

η combustion efficiency

ΔH_w enthalpy rise of water used to quench exhaust gases, Btu/lb original air

ΔH_e	enthalpy rise of exhaust gases, Btu/lb original air
ΔH_j	enthalpy rise of cooling jacket water, Btu/lb original air
H_c	lower heat of combustion of fuel, Btu/lb
f/a	weight fuel-air ratio

and where for mixtures richer than stoichiometric,

$$\Delta H_e = \Delta H_s + \left[(f/a)_e - (f/a)_s\right]\left[(L_v)_{T_i} + C_p(T_e - T_i)\right] \tag{2}$$

where

ΔH_s	enthalpy rise of stoichiometric mixture, Btu/lb original air
$(f/a)_e$	actual weight fuel-air ratio
$(f/a)_s$	stoichiometric weight fuel-air ratio
L_v	latent heat of vaporization of fuel, Btu/lb
T_i	inlet mixture temperature, $^{\circ}R$
C_p	mean heat capacity of fuel, Btu/lb, value of 0.5 assumed for this report
T_e	temperature of exhaust gas, $^{\circ}R$

In this method of determining combustion efficiency, where the reaction products are cooled rapidly to a low temperature, the composition of the exhaust gas is probably frozen at its equilibrium composition at the combustor exit. In this case, the measurable amount of sensible heat in the exhaust gas is less than the net heating value of the fuel by the amount tied up in the dissociated products. This dissociation enthalpy may amount to about 7 percent of the lower heating value at stoichiometric conditions (ref. 2). The combustion efficiencies reported herein include no correction for this effect.

The procedure used in obtaining the stability limits was to set the burner operating in the stable range with the pilot off as mentioned before, and then to reduce fuel flow slowly while maintaining the burner-inlet pressure constant until the burner went out. In the cases where piloting was maintained, the stability limits reported are not blow-out limits but merely the limits of stable burning. Without piloting, there was no region of unstable burning, and the stability limits reported are blow-out limits. The minimum pressure points were obtained by holding the fuel flow constant and slowly lowering the burner-inlet pressure until the flame blew out or the nozzle was wide open and a choking condition existed.

The combustion efficiency and stability limits were determined for the following series of configurations shown in figure 2(c): (1) a single blade mounted perpendicular to the V-gutter at several axial positions, (2) a single blade parallel to the V-gutter at several axial positions, (3) a single blade perpendicular to the V-gutter at several axial positions and blade angles, and (4) a four-blade arrangement consisting of one perpendicular blade at the 1-inch position and three parallel blades at the $2\frac{1}{2}$-, 4-, or $5\frac{1}{2}$-inch positions.

RESULTS AND DISCUSSION

The data obtained in this investigation and discussed herein are presented in table I.

The results of the combustion-efficiency measurements on the series of single perpendicular blade arrangements at inlet pressure of 1 atmosphere, temperature of 660° R, and inlet velocity of 220 feet per second are shown in figure 3, where combustion efficiency is plotted against equivalence ratio for several axial positions of the blade. The ends of these curves do not necessarily mean blow-out was reached. In some instances, only the combustion efficiency near stoichiometric was of interest, and the complete equivalence-ratio range was not investigated. It will be noted that two different burner spools were used, and the combustion efficiency of the V-gutter alone was about 4 percent higher for spool II than for spool I. The greater number of openings in spool II apparently created more flow disturbances than the relatively smooth surface of spool I and thereby caused the slightly higher combustion efficiencies. In subsequent figures, however, the efficiencies obtained with either spool are plotted as determined.

A cross plot of the combustion efficiency at an equivalence ratio of 1.0 against axial location of the blade is given in figure 4. This curve shows the marked effect of blade positioning on the combustion efficiency. An increase of nearly 20 percentage points in combustion efficiency was obtained for the blade located $2\frac{1}{2}$ inches from the gutter over the combustion efficiency of the V-gutter alone. Approaching too close to the flame holder apparently disturbs the normal wake region and can cause deleterious effects on the performance, since a slight drop in combustion efficiency was noted at the 1-inch blade position.

Although the blades were not cooled, they never reached temperatures much above about 2000° R. Thus, though the blade may be serving as a sink for heat or active particles, it is apparently also providing an intensive mixing zone downstream and is promoting greater flame spreading.

The blade close to the gutter also strongly affected the stability limits. Figure 5 shows the fuel-air-ratio limits of stable operation as a function of the inlet pressure for several of the same configurations as shown in figure 4. The inside of the loop represents the operable region; and the outside, the nonoperable region. The V-gutter alone had the widest operable fuel-air-ratio range for a given pressure and the lowest operable pressure. As a blade was inserted and moved toward the flame holder, the operating range was decreased markedly. The operating range may be quite narrow at an inlet pressure of 1 atmosphere with the blade positioned closer to the gutter than 4 inches. This was indeed the case, and on some occasions no operation could be obtained with the blade close to the gutter without auxiliary piloting. This sensitivity was undoubtedly a result of variation in the steadiness of the air supply from one day to another. Comparative plots, however, were all taken during a single operating period whenever possible, so that consistency in the comparisons is maintained.

Reference 1 showed that twelve blades positioned for mixing increased the combustion efficiency over that of the V-gutter alone by about 20 percentage points at an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0. The results of the present investigation show that a single blade, properly located, can increase the combustion efficiency by the same amount, and at the same time introduce a pressure drop across the burner which is considerably less than that incurred by the multiple-blade arrangement of reference 1. However, this result is achieved with a smaller stability range than was obtained with the V-gutter, while the multiple-blade arrangement had a greater stability range than was obtained with the V-gutter alone. Figure 6 shows a comparison of the static-pressure drop of the single-blade configuration and the 12-blade configuration (table II), along with the theoretical pressure losses resulting from heat addition in a constant-area duct with two different values of friction pressure loss upstream of the region of heat addition. These friction pressure losses are expressed in terms of $\Delta p/q$ or the ratio of total-pressure drop to inlet dynamic head. The pressure drop for comparable efficiencies was considerably less for the single-blade configuration. The effect that pressure drops of this order of magnitude would have on the specific fuel consumption of an engine will depend upon the flight conditions the engine will encounter. Analysis for an afterburner case indicated that a change in flame-holder friction pressure loss $\Delta p/q$ from 1 to 3 can be equivalent to losses in combustion efficiency of 6 percent and greater.

Since reference 1 also showed that considerable improvement in stability limits could be obtained with multiple blades placed parallel to the V-gutter, it was desirable to investigate the possibility of using a single parallel blade to produce this same effect also. Figure 7 shows the pressure against equivalence-ratio curve for the V-gutter alone and for three axial positions of a parallel-mounted blade. It is seen that no effect on stability limits resulted from these variations. Although the data are not presented herein, there was no effect for these variations on combustion efficiency, either.

The effect of varying the angle of attack of the blades mounted perpendicular to the V-gutter was also investigated. The angle of attack is here defined as the smallest angle between the axis of the burner and the flat side of the blade (fig. 2(c)). Figure 8 shows the effect of varying the blade angle on combustion efficiency for several blade positions, and figure 9 shows the effect of the blade angle on stability limits for the blade mounted at $2\frac{1}{2}$ inches. As the blade intercepts more of the stream, up to an angle of about 30°, the combustion efficiency is increased. Beyond this angle any further effect is slight. Similarly, as the blade angle is increased, the stability limits are decreased. The limits and efficiency level-off at about the same positioning of the blade.

Since it was shown that one blade, properly located perpendicular to the axis of the V-gutter, could markedly increase the combustion efficiency, and since it has been shown in reference 1 that several blades oriented parallel to the V-gutter increase the stability, it was thought that some combination of parallel and perpendicular blading might improve both the efficiency and stability without prohibitively increasing the pressure drop. Obviously, a large number of variations is possible, and only comparatively few were investigated. In figure 10 the combustion efficiencies of two configurations are compared with that of the V-gutter alone. A combination of one perpendicular blade at the 1-inch position and three parallel blades at the $2\frac{1}{2}$-, 4-, and $5\frac{1}{2}$-inch positions (fig. 2(c)) had a combustion efficiency about 16 percentage points higher than that attained with the V-gutter alone at an inlet pressure of 1 atmosphere, an inlet velocity of 220 feet per second, an inlet temperature of 660° R, and an equivalence ratio of 1.0. At the same conditions, a single blade at the 4-inch position had a combustion efficiency about 18 percentage points higher than that attained with the V-gutter. A comparison of the stability limits of these same configurations (fig. 11) shows that the configuration with four blades, while not as stable as the V-gutter alone, has improved limits over the single-blade configuration.

Pressure fluctuations imposed upon a burner may be either attenuated or amplified, according to reference 3. The tendency to amplify pressure fluctuations (and, therefore, probably to decrease stability) increased with temperature ratio across the burner and with lower-pressure-loss flame holders. This amplification tendency may be the reason that the high-efficiency, low-pressure-loss single-blade configuration is less stable than the V-gutter, while the high-pressure-loss multiple-blade configuration is more stable than the V-gutter.

The stability limits reported herein have all been with no auxiliary piloting. The stability limits may be improved considerably by maintaining a small amount of piloting in the sheltered zone (table III). Figure 12, for example, shows the marked improvement in stability possible with pilot heats equal to 0.7 and 1 percent of the net heating value of the stoichiometric fuel-flow rate with the V-gutter alone and with the gutter plus one perpendicular blade at the $5\frac{1}{2}$-inch position. The stability curves shown for the piloted case are not blow-out limits but merely rough-burning limits, while the nonpiloted curves are blow-out limits. The V-gutter with only 0.7-percent pilot heat operated stably at choking conditions and 0.3 atmosphere, whereas the minimum operable pressure without pilot was about 0.46 atmosphere.

An increase in pilot heat to 1 percent widened the smooth-burning range considerably. A similar increase in the stable-burning range was noted for the gutter-plus-blade configuration (fig. 12(b)), where without pilot the lowest operable pressure was about 0.67 atmosphere, and with 0.7-percent pilot the burner was still operating smoothly at a choked condition at 0.57 atmosphere.

The results reported herein were all taken with cooled combustor walls and with blades that, while not internally cooled, never got much above about 2000° R, since they were mounted in the cooled spool section and lost heat by conduction. It is possible that the stability and efficiency effects of these blades might be altered if the surfaces were allowed to approach flame temperature.

SUMMARY OF RESULTS

The following results were obtained in a 5-inch-diameter ram-jet combustor with various arrangements of flame-immersed surfaces:

1. A single blade mounted perpendicular to and downstream of the V-gutter had a marked effect on the stability and efficiency of the burner, depending on its axial location.

2. The same increase in combustion efficiency was obtained with a single blade as had been obtained previously with a multiple-blade configuration, with a resulting considerably smaller pressure loss.

3. The highest combustion efficiency with a single flame-immersed blade was obtained with the blade at a position $2\frac{1}{2}$ inches from the gutter. With this configuration, the combustion efficiency was about 80 percent; whereas the combustion efficiency was about 60 percent without the flame-immersed blade.

4. As a single blade mounted perpendicular to the flame holder approached the flame holder, the stability limits without auxiliary piloting became poorer.

5. A single blade mounted parallel to the V-gutter had no effect on the stability limits or efficiency at any of the locations investigated.

6. A small amount of continuous pilot heat effected large improvements in stability limits.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 22, 1954

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TABLE I. - SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, ^{o}R	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg
V-Gutter; no blade; spool I							
1.820	1.0	652	214	0.902	59.3		5.05
1.825		646	213	.963	60.1		5.4
1.825		643	212	1.024	59.9		5.8
1.825		638	210	1.092	57.9		6.15
1.830		636	210	1.152	55.0		6.35
1.825		632	208	1.220	51.5		6.45
1.825		628	207	1.286	47.0		6.45
1.825		628	207	1.350		Rich	
1.825		649	214	.900	60.0		5.1
1.830		650	214	.836	59.8		4.65
1.830	↓	650	214	.777	58.4		
1.580	.833	661	226	.804		Lean	
1.585	.833	635	218	1.330		Rich	
1.310	.667	659	234	.846		Lean	
1.320	.667	638	228	1.272		Rich	
1.320	.667	639	228	1.257		Rich	
.985	.500	653	232	.960		Lean	
.980	.500	644	228	1.152		Rich	
.870	.45	647	226	1.092		Press.[a]	
.900	.467	647	225	1.096		Lean	
1.27	.67	661	227	.873		Lean	
1.30	.67	643	225	1.251		Rich	
.96	.50	653	225	1.004		Lean	
.90	.50	643	209	1.190		Rich	
.98	.50	657	231	.962		Lean	
.90	.46	652	229	1.058		Press.[a]	
1.06	.58	664	218	.896		Lean	
1.06	.58	648	211	1.240		Rich	
1.55	.83	674	226	.820		Lean	
1.56	.83	646	218	1.324		Rich	
1.82	1.01	672	220	.778		Lean	
1.82	1.0	644	213	1.354		Rich	
[b]1.78	1.0	656	211	1.049	63.3		6.85
[b]1.80	1.0	658	214	.956	65.6		6.25
[b]1.80	1.0	651	211	1.128	60.8		7.25

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[a] Minimum pressure.

[b] Spool II.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, $^{\circ}R$	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg	Angle of attack, deg
V-Gutter and one perpendicular blade at 1-in. position; spool I								
1.810	1.0	652	213	1.034	75.0		9.85	
1.840		650	216	.956	78.0		9.45	
1.820		651	214	.902	79.5		8.65	
1.820		651	214	.836		Lean		
1.820		650	214	.922	78.9		8.85	
1.830		646	213	1.023	76.4		10.0	
1.825		642	211	1.092	73.2		10.4	
1.825		638	210	1.155	69.0		10.50	
1.825		651	214	1.210		Rich		
1.825		650	214	.900	78.2		8.65	
1.825		650	214	.858	77.9		8.1	
1.825		646	212	.984	77.5		9.55	
1.80		656	214	1.036	64.4		6.60	0
1.80		657	214	1.036	73.1		8.3	15
1.80		657	212	1.042	76.6		9.1	30
V-Gutter and one perpendicular blade at 2.5-in. position; spool I								
1.735	1.0	683	214	0.946	81.3		8.1	
1.800		661	215	.912	80.1		8.55	
1.800		656	213	.977	79.6		9.1	
1.800		652	212	1.040	77.5		9.65	
1.800		648	210	1.107	73.6		10.05	
1.800		648	210	1.148		Rich		
1.810		657	214	.908	80.1			
1.810		657	214	.908		Lean		
1.84		653	215	1.02	84.6		11.6	90
1.82		653	214	1.028	84.1		11.50	90
1.82		654	215	1.028	83.9		11.30	75
1.81		654	214	1.034	84.2		11.10	60
1.81		653	213	1.034	83.3		10.95	45
1.82		652	214	1.028	83.3		10.65	30
1.82		653	214	1.030	80.5		9.8	15
1.82		654	215	1.028	73.5		8.25	0

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, °R	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg	Angle of attack, deg
V-Gutter and one perpendicular blade at 4-in. position; spool I								
1.74	1.02	671	206	0.946	78.3		7.5	
1.73	1.0	670	209	.950	78.6		7.55	
1.73	↓	666	208	1.017	77.4		8.00	
1.74	↓	662	207	1.078	74.2		8.3	
1.73	↓	660	206	1.152	68.8		8.45	
1.73	↓	660	206	1.173		Rich		
1.73	↓	674	210	.951	78.4		7.55	
1.73	↓	675	210	.886	81.6		7.0	
1.73	↓	678	211	.843	81.3		6.55	
1.73	↓	678	211	.800		Lean		
1.78	↓	663	212	.840		Lean		
1.80	↓	649	211	1.128		Rich		
1.79	↓	663	214	.855		Lean		
1.54	.83	659	220	.963		Press.[a]		
1.54	.83	658	219	1.017		Press.[a]		
1.67	.90	667	223	.885		Lean		
1.67	.90	660	221	1.053		Rich		
1.82	1.0	654	214	1.03	60.2		5.9	0
1.82	↓	644	211	1.03	72.8		8.2	30
1.81	↓	644	210	1.034	75.0		8.65	45
1.80	↓	645	210	1.036	75.8		8.9	60
1.82	↓	644	212	1.024	76.1		9.1	75
1.82	↓	648	212	1.030	69.0		7.3	15
1.80	↓	646	210	1.036	62.2		5.95	0
1.81	↓	666	217	.789		Lean		45
1.80	↓	645	210	1.227		Rich		45
1.80	↓	678	220	.771		Lean		0
1.80	↓	652	211	1.316		Rich		0
1.80	↓	676	219	.808		Lean		30
1.80	↓	657	213	1.218		Rich		30
1.80	↓	675	218	.831		Lean		60
1.80	↓	675	218	.843		Lean		60
1.80	↓	661	214	1.131		Rich		60
1.80	↓	662	214	1.112		Rich		60
1.54	.83	680	226	.790		Lean		0

[a] Minimum pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, °R	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg	Angle of attack, deg
V-Gutter and one perpendicular blade at 4-in. position; spool I								
1.54	0.83	656	218	1.298		Rich		0
1.53	↓	685	227	.825		Lean		30
1.53	↓	669	222	1.158		Rich		30
1.53	↓	683	226	.864		Lean		60
1.53	↓	673	222	1.095		Rich		60
1.28	.67	682	235	.846		Lean		0
1.28	.67	663	230	1.238		Rich		0
1.28	.67	673	227	1.022		Press.[a]		30
1.40	.75	671	226	.88		Lean		30
1.40	.75	659	223	1.095		Rich		30
1.54	.85	670	220	.957		Press.[a]		60
.93	.52	657	213	1.138		Press.[a]		0
1.08	.58	668	224	.918		Lean		0
1.09	.58	657	221	1.200		Rich		0
V-Gutter and one perpendicular blade at 5.5-in. position; spool I								
1.76	1.0	646	205	0.933	75.8		7.2	
1.76	↓	646	204	1.002	74.9		7.5	
1.75	↓	644	203	1.070	72.4		7.8	
1.74	↓	642	202	1.144	67.3		7.9	
1.74	↓	640	202	1.208	61.7		7.9	
1.74	↓	640	202	1.252		Rich		
1.74	↓	658	206	.944	76.5		7.1	
1.74	↓	661	207	.879	78.4		6.5	
1.75	↓	670	211	.814	75.4		5.9	
1.75	↓	670	211	.783		Lean		
1.79	1.01	674	216	.801		Lean		
1.79	1.0	652	211	1.221		Rich		
1.55	.84	671	224	.825		Lean		
1.55	.83	656	220	1.158		Rich		
1.54	.83	657	219	1.161		Rich		
1.54	.83	676	225	.825		Lean		
1.26	.67	674	229	.900		Lean		
1.26	.67	664	227	1.050		Rich		
1.28	.67	663	229	1.035		Rich		
1.18	.62	660	228	1.017		Press.[a]		

[a] Minimum pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, $^{\circ}$R	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg	Angle of attack, deg
V-Gutter and one perpendicular blade at 5.5-in. position; spool I								
1.18	0.63	663	222	0.926		Lean		
1.12	.61	655	219	1.004		Press.[a]		
1.82	1.0	654	214	1.028	63.5		6.45	0
1.83		651	215	1.023	72.0		7.9	15
1.82		650	214	1.024	73.7		8.20	30
1.82		650	213	1.03	74.6		8.45	45
1.82		650	213	1.028	74.8		8.60	60
1.82		650	214	1.024	75.0		8.75	90
1.82		650	213	1.030	65.6		6.45	0
V-Gutter and one perpendicular blade at 7.5-in. position; spool II								
1.76	1.0	651	207	1.064	73.3		8.5	
1.76		654	208	.996	76.5		8.05	
1.76		656	208	.933	78.2		7.55	
1.76		660	209	.868	78.7		7.0	
1.76		664	211	.807	78.3		6.35	
1.76		676	215	.746		Lean		
1.76		653	207	1.064	72.3		8.40	
1.76		648	206	1.131	67.8		8.65	
1.76		643	204	1.198	62.0		8.75	
1.76		650	206	1.264		Rich		
1.30	.67	664	233	.882		Lean		
1.30	.67	649	227	1.180		Rich		
1.08	.58	657	220	.938		Lean		
1.09	.58	649	219	1.108		Rich		
.96	.53	650	212	1.038		Press.[a]		
.95	.55	652	204	.996		Press.[a]		
.96	.57	647	197	1.100		Press.[a]		
V-Gutter and one perpendicular blade at 11.5-in. position; spool II								
1.78	1.0	660	211	0.861	76.3		6.9	
1.76		651	207	1.064	71.4		8.25	
1.76		654	208	.996	74.2		7.85	
1.76		658	210	.930	75.9		7.4	
1.77		661	211	.864	76.7		6.85	

[a] Minimum pressure.

TABLE I. - Continued. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, °R	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg
V-Gutter and one perpendicular blade at 11.5-in. position; spool II							
1.76	1.0	665	212	0.806	76.4		6.35
1.76		675		.748		Lean	
1.77		652	208	1.058	71.4		8.25
1.77		649	207	1.125	67.3		8.60
1.77		645	206	1.191	62.7		8.7
1.77	↓	652	208	1.257		Rich	
V-Gutter and one perpendicular blade at 15-in. position; spool II							
1.78	1.0	657	210	1.055	69.3		8.25
1.78		656	210	.990	71.7		7.85
1.78		650	208	1.122	66.2		8.70
1.78		676	216	.756		Lean	
1.78	↓	652	209	1.259		Rich	
V-Gutter and one perpendicular blade at 24-in. position; spool II							
1.80	1.0	656	213	1.040	65.6		8.5
1.80		660	214	.956	68.2		7.7
1.80		652	212	1.128	62.6		9.05
1.80		651	211	1.326		Rich	
1.80	↓	679	220	.768		Lean	
V-Gutter and one parallel blade at 1-in. position; spool I							
1.295	0.667	657	230	0.862		Lean	
1.295	.667	657	230	.856		Lean	
1.290	.667	636	222	1.286		Rich	
.950	.500	648	222	.974		Lean	
.950	.500	639	219	1.167		Rich	
.945	.500	640	218	1.150		Rich	
.940	.500	644	218	1.161		Rich	
.935	.500	656	221	.932		Lean	
.940	.48	653	230	.975		Press.[a]	
1.550	.833	670	225	.788		Lean	
1.56	.833	644	218	1.324		Rich	
1.810	1.00	669	218	.780		Lean	
1.820	1.00	640	210	1.358		Rich	
1.330	.667	657	236	.878		Lean	
1.310	.667	657	233	.884		Lean	
1.310	.667	638	226	1.252		Rich	

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[a] Minimum pressure.

TABLE I. - Concluded. SUMMARY OF PERFORMANCE DATA

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, $^{\circ}R$	Inlet velocity, ft/sec	Equivalence ratio	Combustor efficiency, percent	Blow-out	Static-pressure drop, Δp, in. Hg
V-Gutter and one parallel blade at 2.5-in. position; spool I							
1.315	0.667	654	233	0.880		Lean	
1.320	.667	635	227	1.272		Rich	
.960	.500	647	224	.933		Lean	
.950	.500	635	218	1.180		Rich	
.895	.463	640	223	1.062		Press.[a]	
1.555	.833	661	222	.798		Lean	
1.590	.833	635	218	1.336		Rich	
1.820	1.0	662	217	.736		Lean	
1.835	1.0	632	209	1.338		Rich	
V-Gutter and one parallel blade at 5.5-in. position; spool I							
1.625	0.833	650	229	0.777		Lean	
1.630	.833	624	220	1.317		Rich	
1.855	1.0	649	217	.746		Lean	
1.860	1.0	618	207	1.352		Rich	
1.315	.667	641	228	.830		Lean	
1.290	.667	618	216	1.288		Rich	
.955	.50	637	219	.898		Lean	
.970	.50	624	218	1.178		Rich	
V-Gutter and one perpendicular blade at 1-in. position and three parallel blades at 2.5-, 4-, and 5.5-in. positions; spool I							
1.80	1.0	647	210	0.976	75.2		8.7
1.80		651	212	.909	76.9		8.05
1.80		655	213	.849	76.9		7.25
1.80		659	214	.789	74.9		6.4
1.80		658	214	.780		Lean	
1.80		648	210	1.039	75.0		9.25
1.80		645	209	1.108	70.9		9.55
1.80		641	208	1.170	66.8		9.55
1.80		647	210	1.222		Rich	
1.46	.833	648	205	1.203		Rich	
1.47	.833	667	212	.807		Lean	
1.175	.67	650	206	1.14		Rich	
1.175	.67	662	210	.900		Lean	
1.175	.61	660	229	.925		Press.[a]	

[a] Minimum pressure.

TABLE II. - PRESSURE DROP DATA ON CONFIGURATION VII OF REFERENCE 1

Equivalence ratio	Pressure drop, Δp, in. Hg	Temperature ratio across burner	Combustor efficiency, percent
0.771	10.6	4.90	79.7
.819	11.2	5.21	82.2
.860	12.1	5.31	80.8
.903	12.7	5.52	82.0
.944	13.5	5.62	81.2
.988	14.0	5.72	79.1
1.032	14.5	5.76	76.7
.771	10.3	5.10	81.4
.73	10.0	4.77	80.8
.765	10.7	5.09	85.4
.724	10.0	4.83	83.8
.801	11.6	5.31	86.4
.850	12.4	5.50	86.5
.891	13.4	5.67	86.6
.932	14.2	5.78	85.3
.974	15.0	5.88	84.3
1.015	15.9	5.95	81.7

TABLE III. - PERFORMANCE DATA WITH PILOT HEAT VARIATION

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, °R	Inlet velocity, ft/sec	Equivalence ratio	Blow-out[a]	Pilot heat, percent
V-Gutter, no blade; spool I						
1.815	1.0	652	214	0.831	Lean	0
		627	205	1.352	Rich	0
		653	214	.814	Lean	0
		653	214	.814	Lean	0
1.819		653	214	.768	Lean	0.7
1.819		653	214	.782	Lean	.7
		623	204	1.395	Rich	.7
		623	204	1.404	Rich	.7
1.188	.67	646	208	.898	Lean	0
1.188	.67	646	208	.898	Lean	0
1.180		629	201	1.288	Rich	0
		651	208	.830	Lean	.7
		627	200	1.346	Rich	.7
.877	.50	641	203	.984	Lean	0
.877		640	202	1.012	Lean	0
.875		631	199	1.185	Rich	0
1.800	1.0	686	223	.813	Lean	0
		661	215	1.341	Rich	0
		690	224	.741	Lean	.7
		657	213	1.414	Rich	.7
.924	.50	668	223	1.014	Lean	0
		668	222	1.024	Lean	0
		657	219	1.146	Rich	0
		670	223	.879	Lean	.7
.925		650	217	1.262	Rich	.7
.925		658	220	1.082	Press.[a]	0
		653	218	1.122	Press.[a]	0
.926	.30	652	363	1.080	(b)	.7

[a] With pilot, limits are smooth-burning limits, not actual blow-out; nonpiloted points are actual blow-outs. "Press." is minimum pressure.

[b] Still burning; choked condition with exhaust nozzle wide open.

TABLE III. - Concluded. PERFORMANCE DATA WITH PILOT HEAT VARIATION

Air flow, lb/sec	Inlet static pressure, atm	Inlet mixture temperature, $^{\circ}$R	Inlet velocity, ft/sec	Equivalence ratio	Blow-out[a]	Pilot heat, percent
V-Gutter, 1 perpendicular blade at 5.5-in. position; spool I						
1.86	1.0	656	220	0.862	Lean	0
1.87		637	214	1.252	Rich	0
1.87		658	222	.819	Lean	0.7
1.83		669	221	.804	Lean	.7
1.83		646	213	1.296	Rich	.7
1.41	.80	674	214	.860	Lean	0
1.40		657	207	1.218	Rich	0
1.38		684	212	.784	Lean	.7
1.41		665	211	1.286	Rich	.7
1.41		688	219	.816	Lean	.7
1.41		689	219	.801	Lean	.7
1.34	.75	663	214	1.266	Rich	.7
1.33		685	219	.820	Lean	.7
		680	218	.912	Lean	0
		667	213	1.184	Rich	0
	.57	671	281	1.040	(b)	.7
1.18	.67	679	217	.855	Lean	.7
1.17	.67	664	210	1.182	Rich	.7
V-Gutter alone, no blade; spool I						
1.86	1.0	682	228	0.674	Lean	1.0
1.86	1.0	645	216	1.444	Rich	1.0
1.36	.77	679	217	.699	Lean	1.0
1.36	.77	645	206	1.394	Rich	1.0
.90	.50	665	216	.814	Lean	1.0
.90	.50	641	208	1.310	Rich	1.0
.90	.28	653	379	1.056	(b)	1.0

[a] With pilot, limits are smooth-burning limits, not actual blow-out; nonpiloted points are actual blow-outs. "Press." is minimum pressure.

[b] Still burning; choked condition with exhaust nozzle wide open.

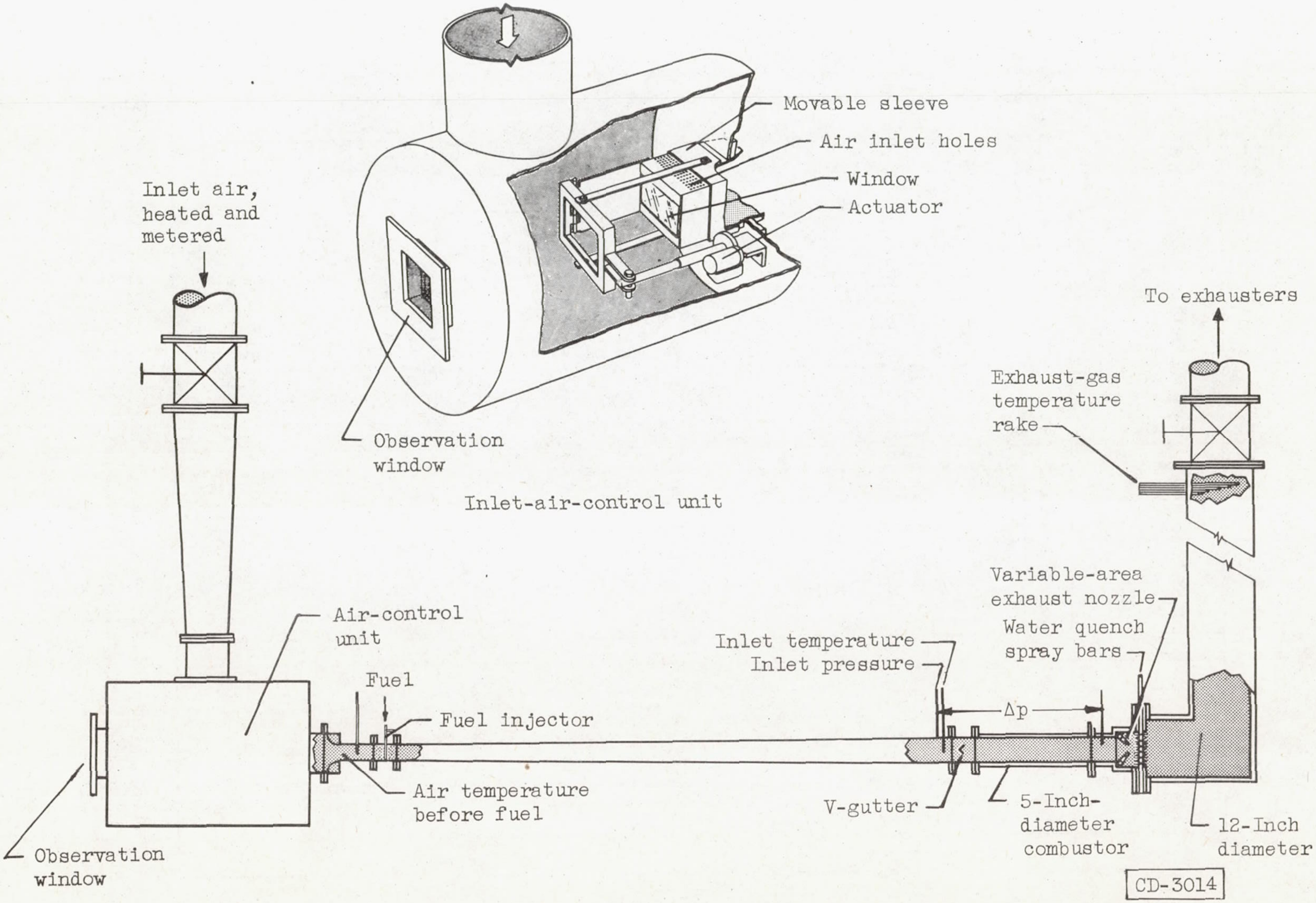
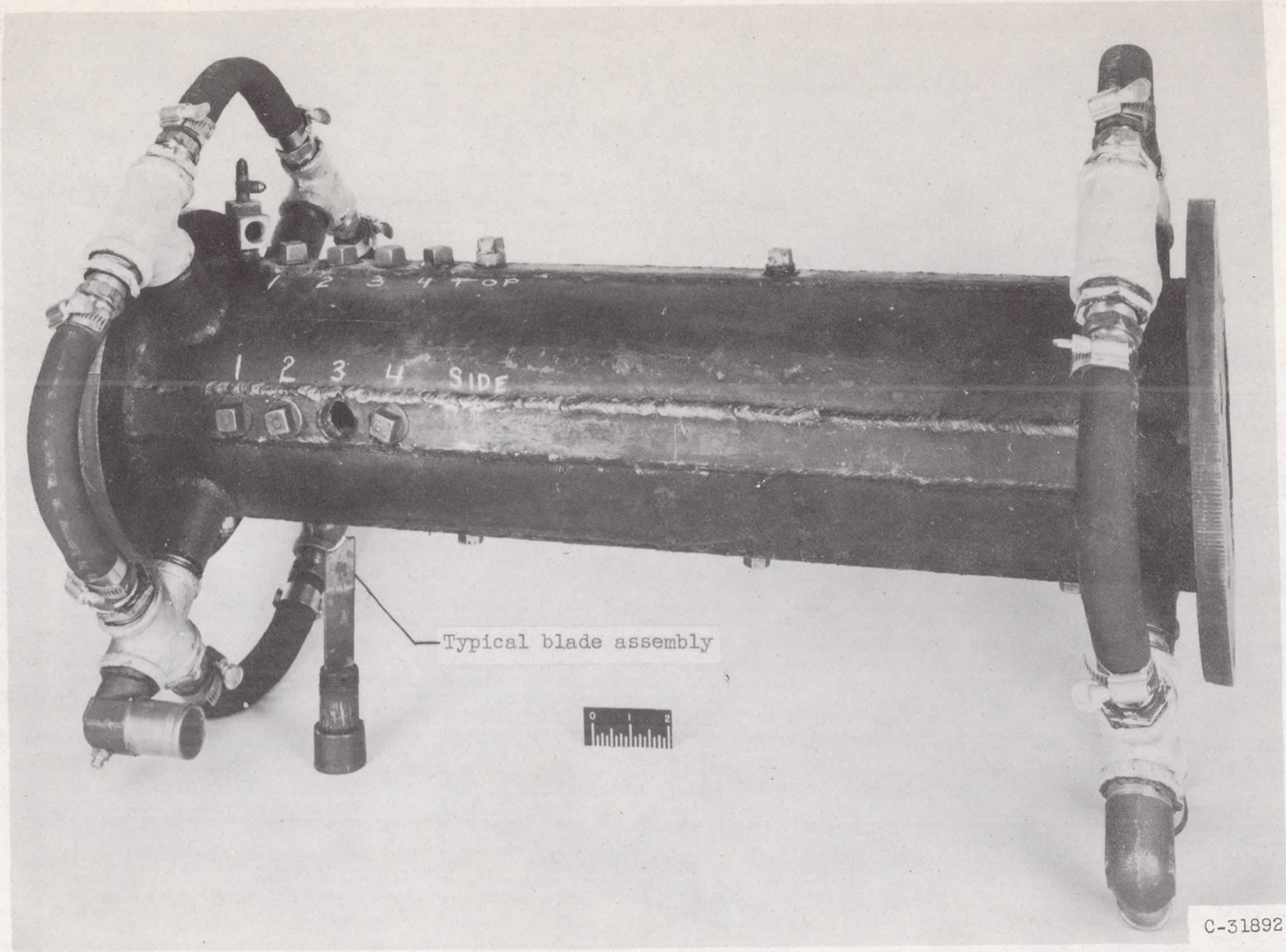
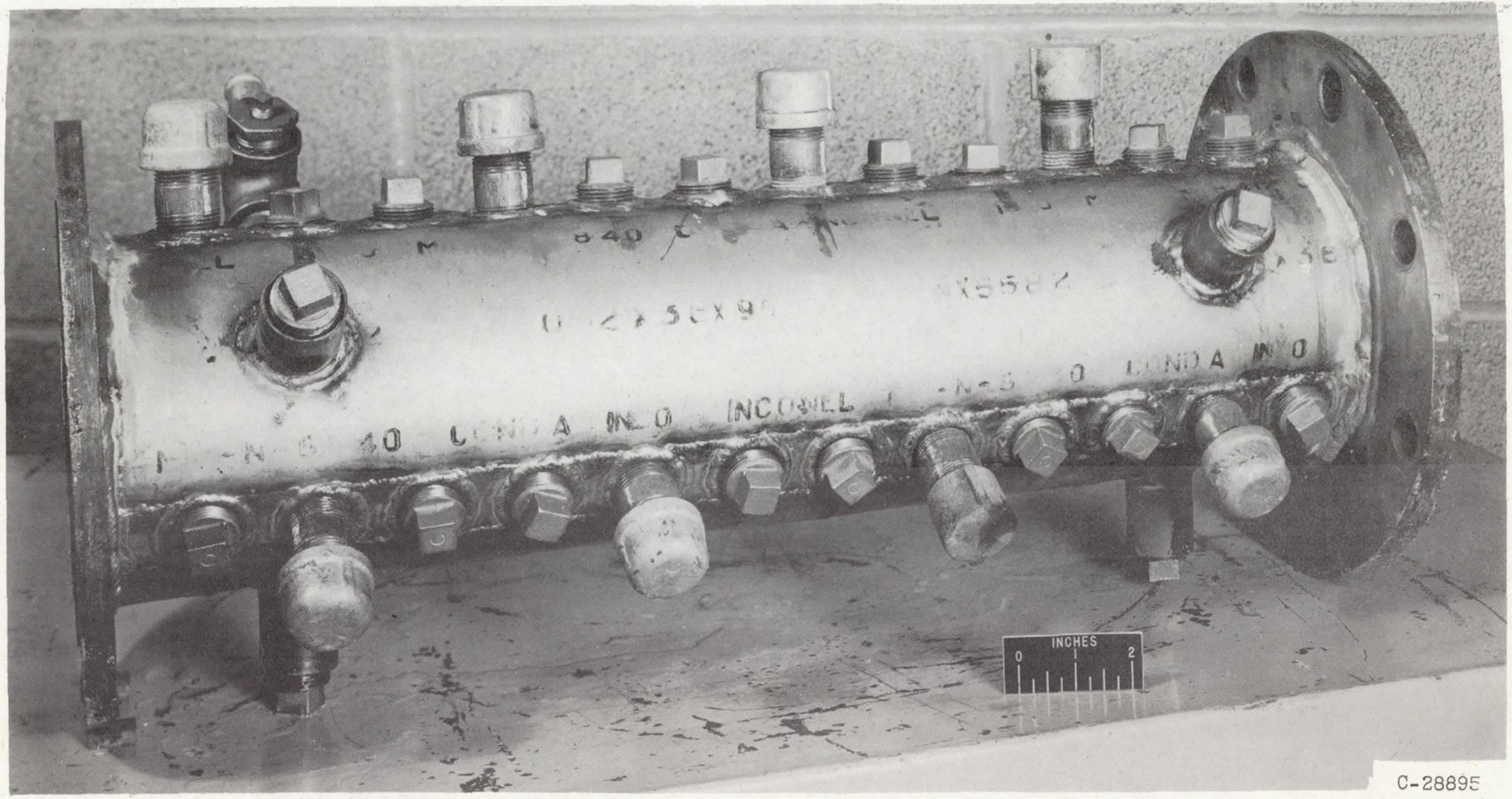


Figure 1. - Schematic illustration of 5-inch-diameter ram-jet combustor setup.



(a) Burner spool I.

Figure 2. - Details of burner configurations investigated.



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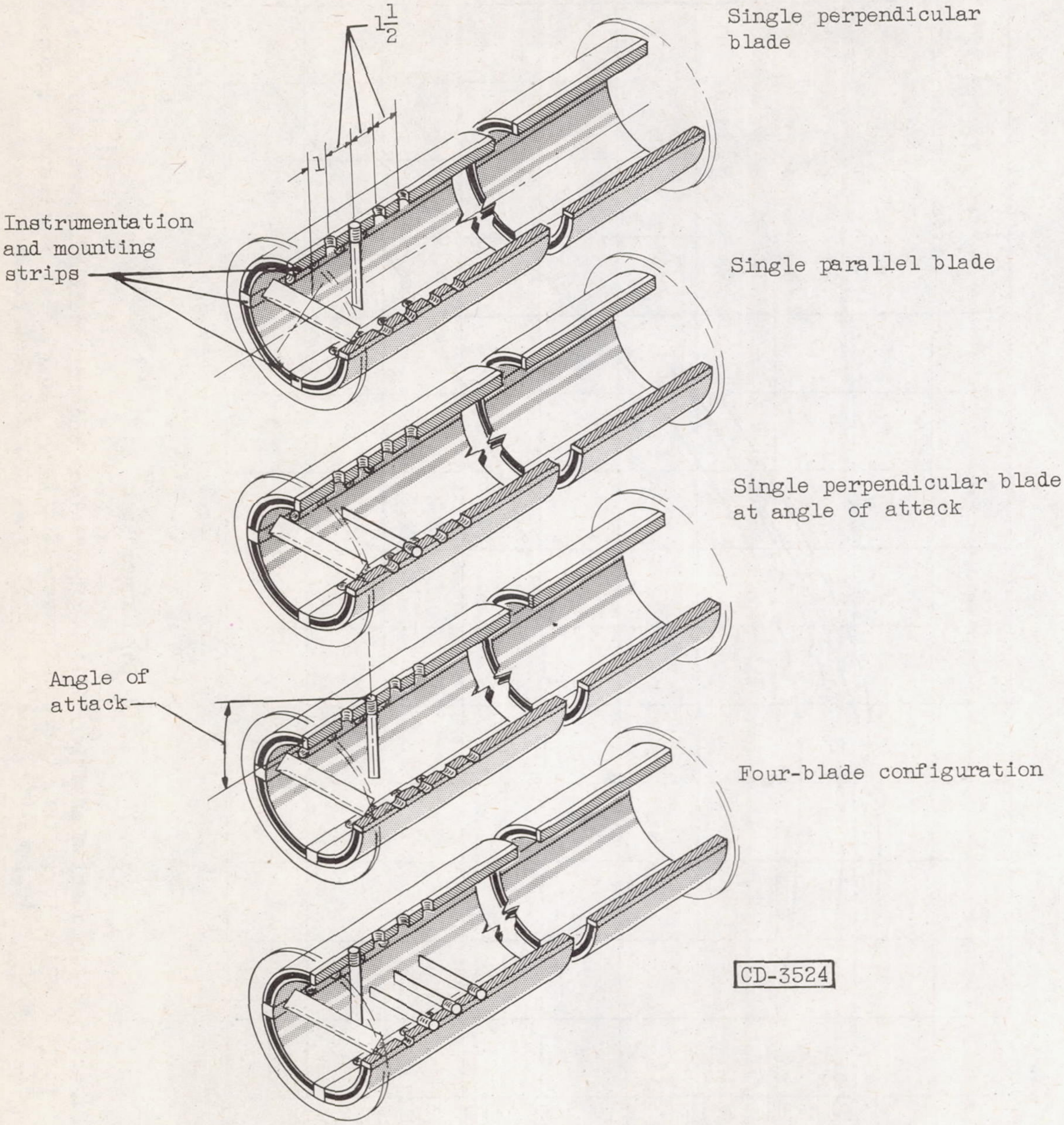
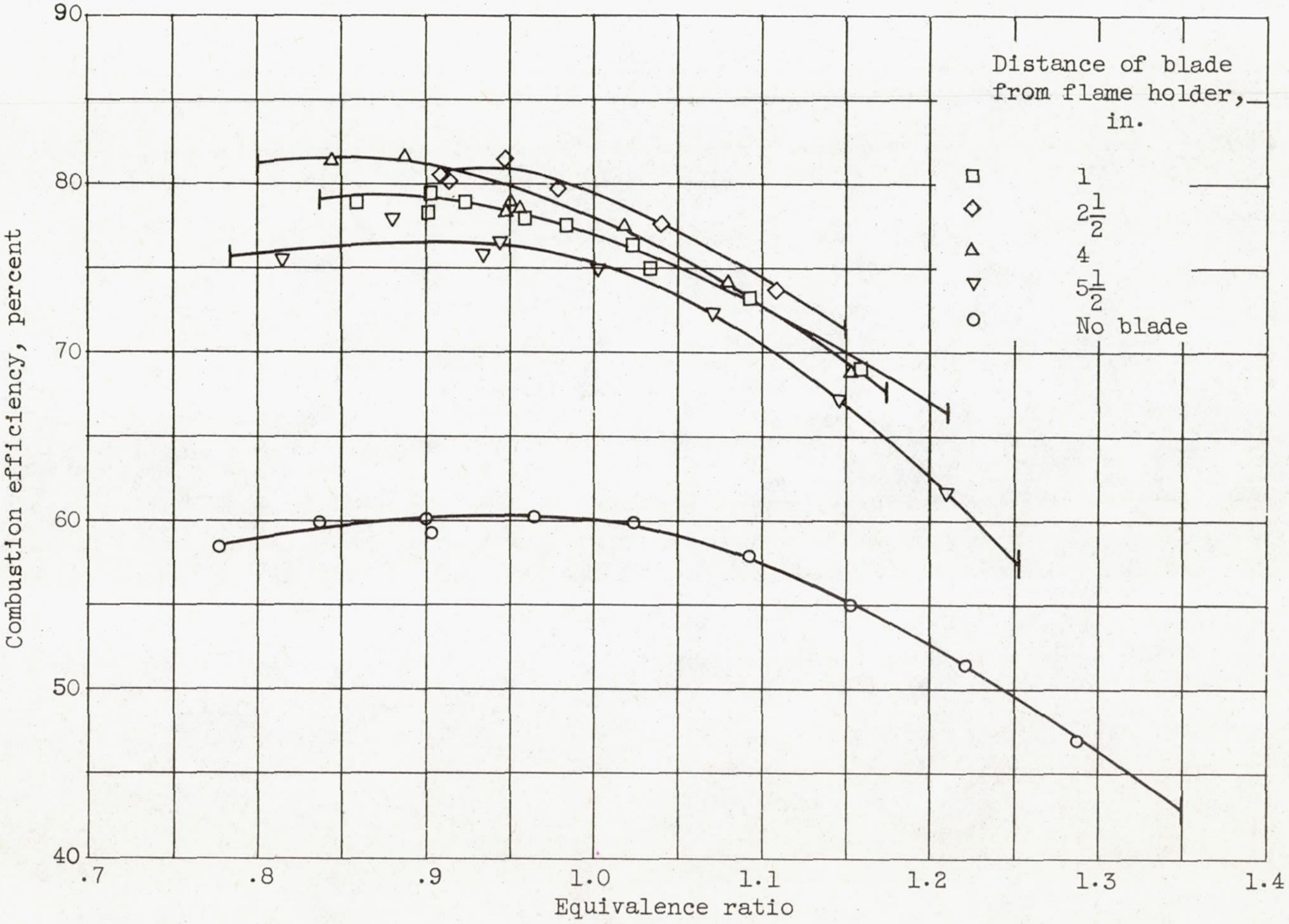
(b) Burner spool II.

Figure 2. - Continued. Details of burner configurations investigated.



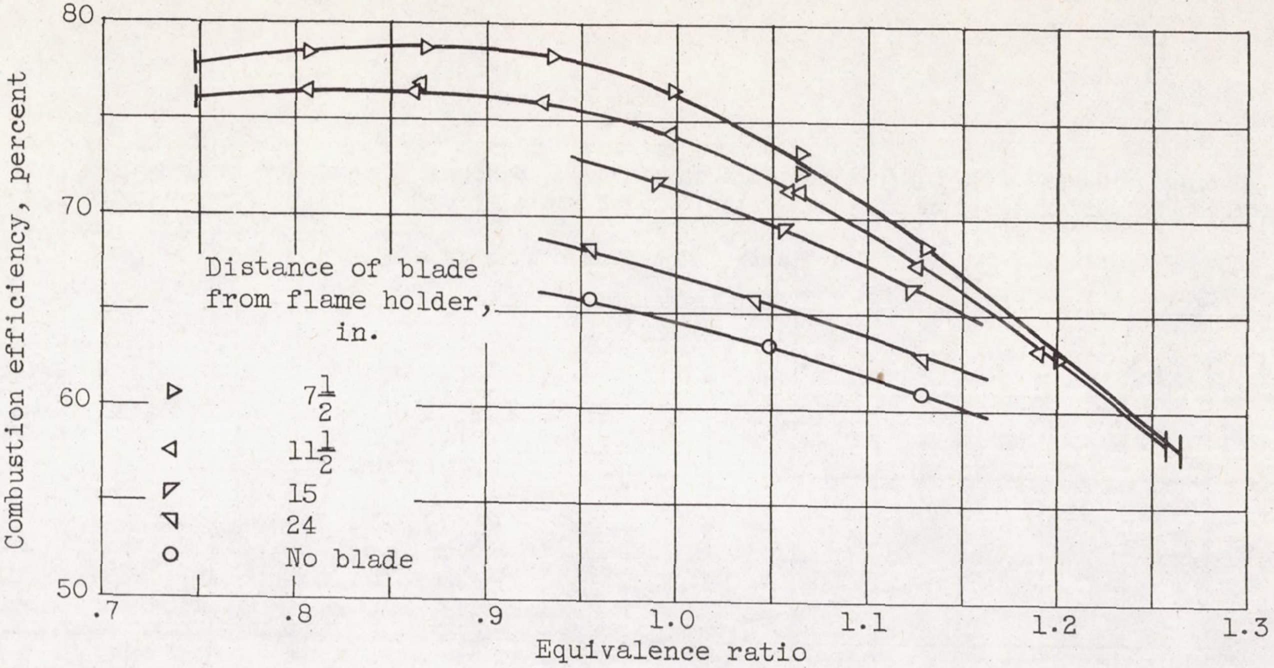
(c) Blade arrangements (dimensions in inches).

Figure 2. - Concluded. Details of burner configurations investigated.



(a) Burner spool I.

Figure 3. - Combustion efficiency of V-gutter alone and in combination with a single blade perpendicular to gutter at several axial locations. Inlet static pressure, 1 atmosphere; inlet mixture temperature, 660° R; inlet velocity, 220 feet per second.



(b) Burner spool II.

Figure 3. - Concluded. Combustion efficiency of V-gutter alone and in combination with a single blade perpendicular to gutter at several axial locations. Inlet static pressure, 1 atmosphere; inlet mixture temperature, 660° R; inlet velocity, 220 feet per second.

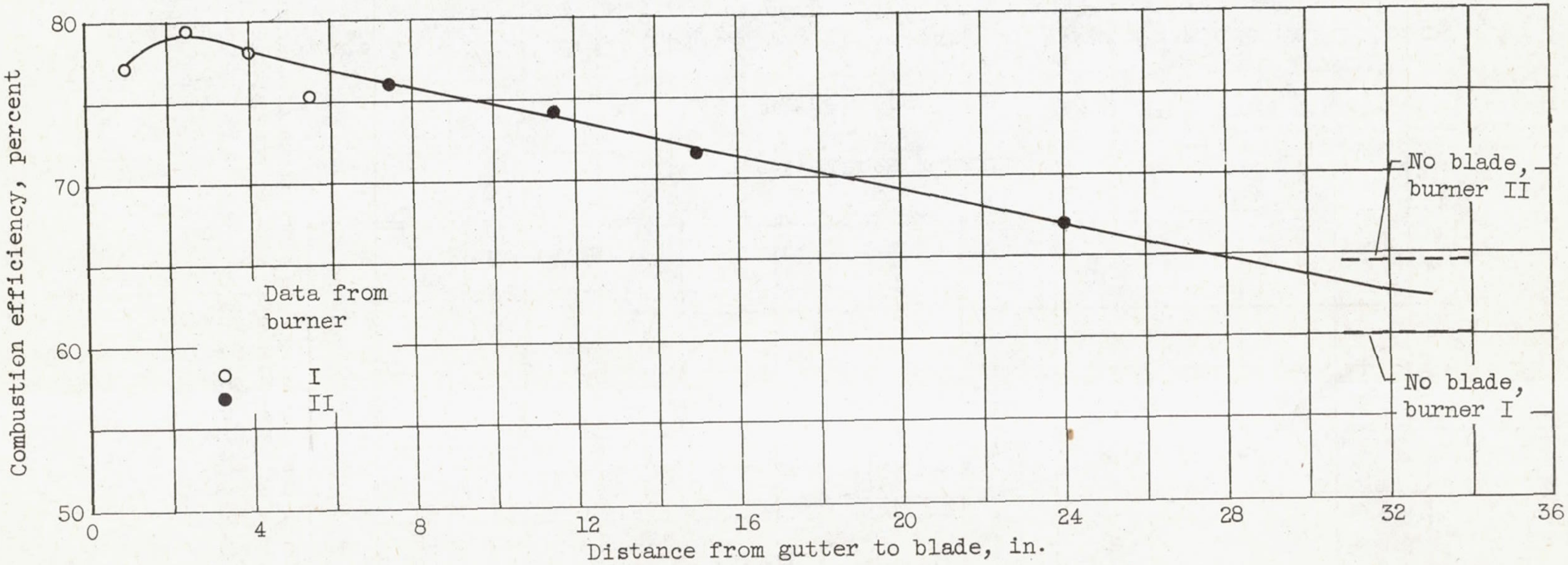


Figure 4. - Effect of axial position of single blade perpendicular to V-gutter flame holder on combustion efficiency of 5-inch-diameter ram-jet combustor. Equivalence ratio, 1.0; inlet pressure, 1 atmosphere; inlet temperature, 660° R; inlet velocity, 220 feet per second.

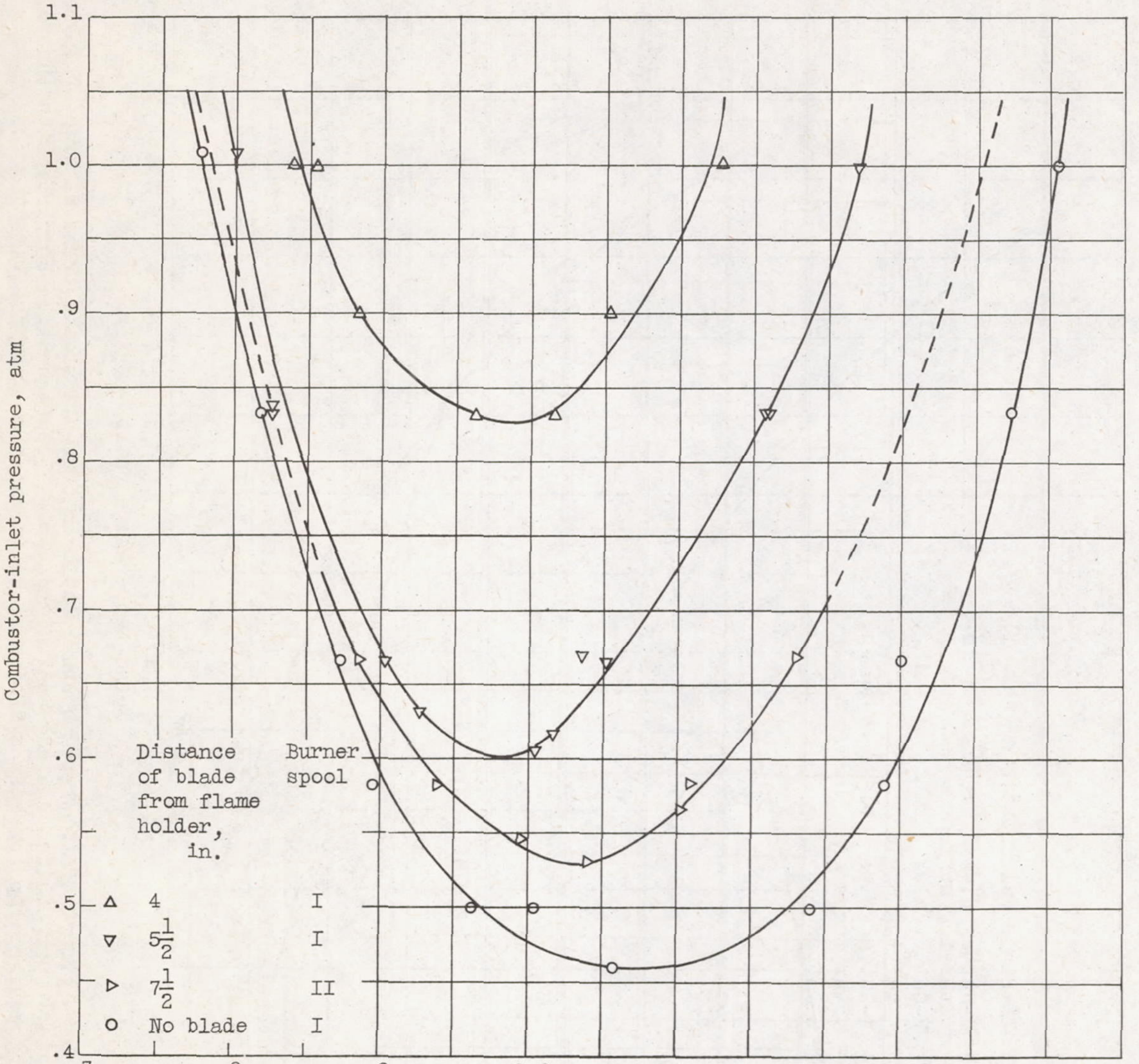


Figure 5. - Effect of axial position of single blade perpendicular to V-gutter flame holder on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second.

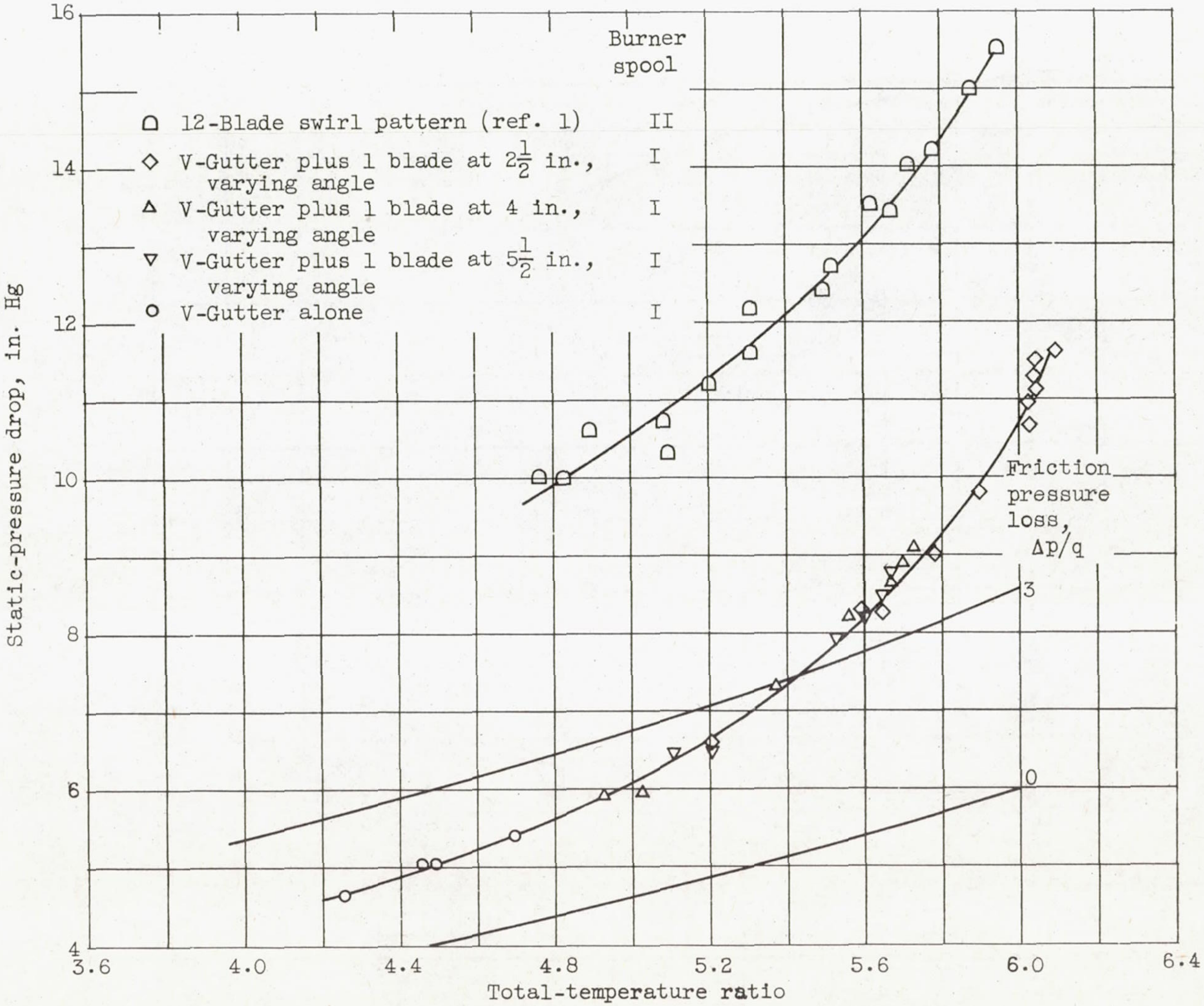


Figure 6. - Effect of total-temperature ratio on over-all static-pressure drop of burner for single perpendicular blade and multiple-blade configuration compared with theoretical pressure drop for heat addition alone in constant-area duct.

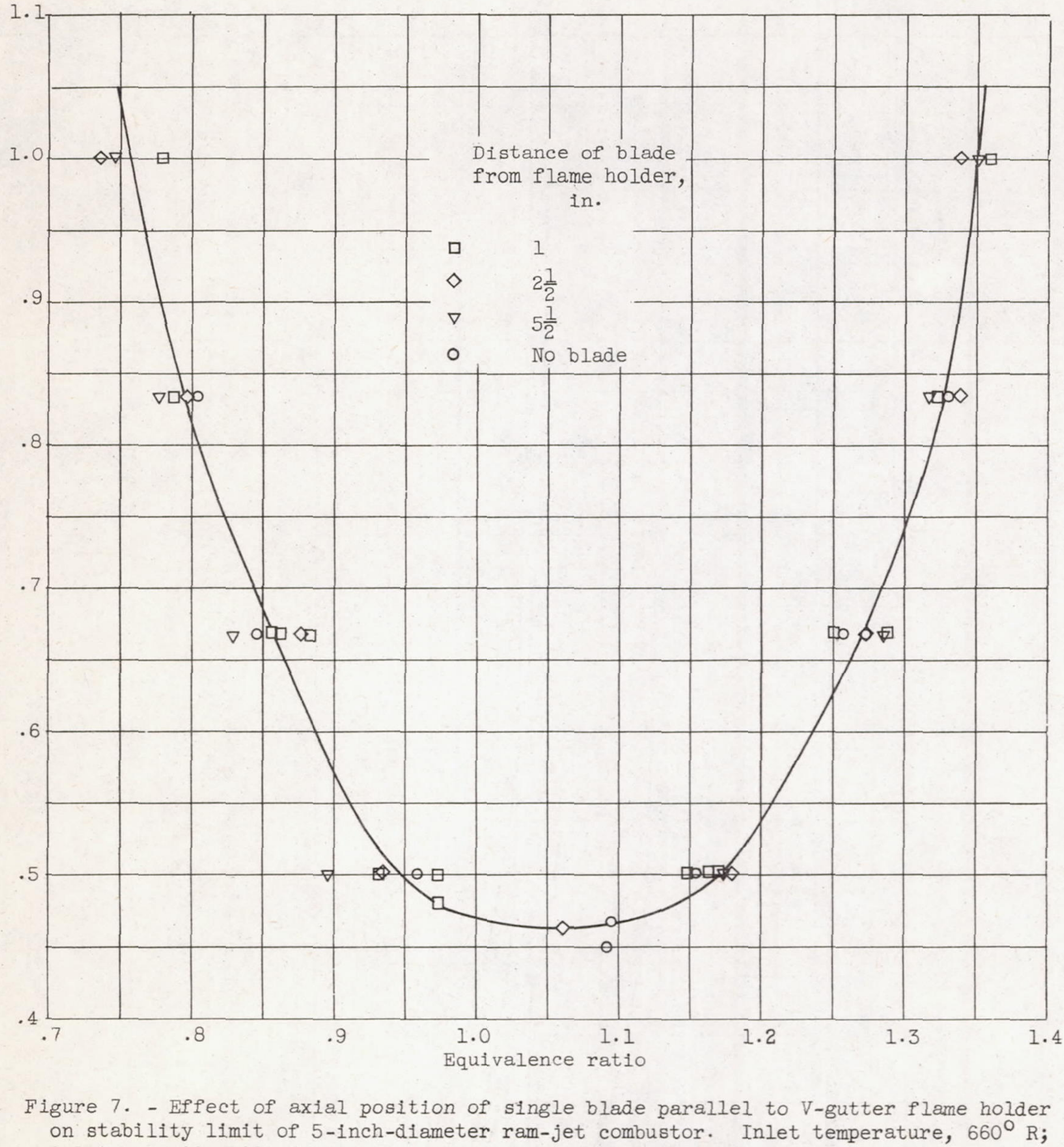


Figure 7. - Effect of axial position of single blade parallel to V-gutter flame holder on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.

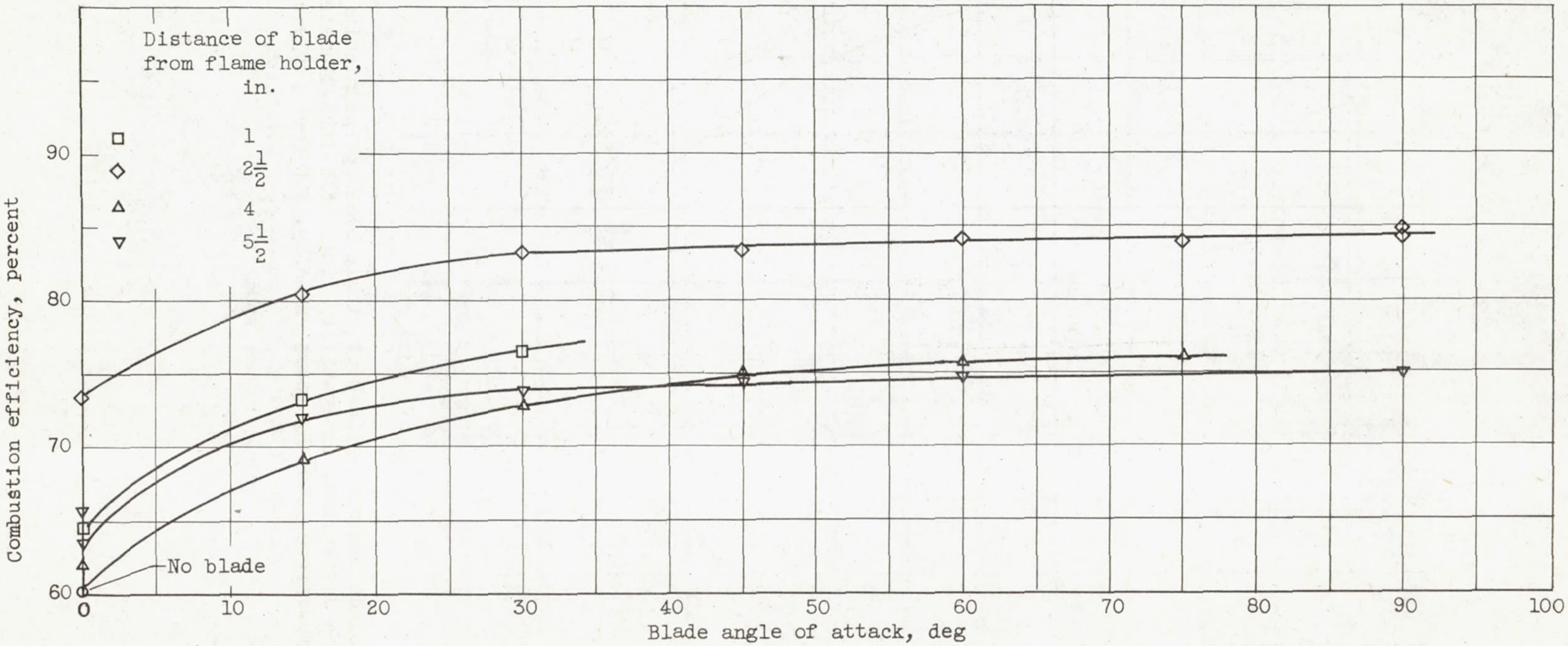


Figure 8. - Effect of blade angle of attack of single blade perpendicular to flame holder on combustion efficiency of 5-inch-diameter ram-jet combustor. Inlet static pressure, 1 atmosphere; inlet temperature, 560° R; inlet velocity, 220 feet per second; equivalence ratio, approximately 1.03; burner spool I.

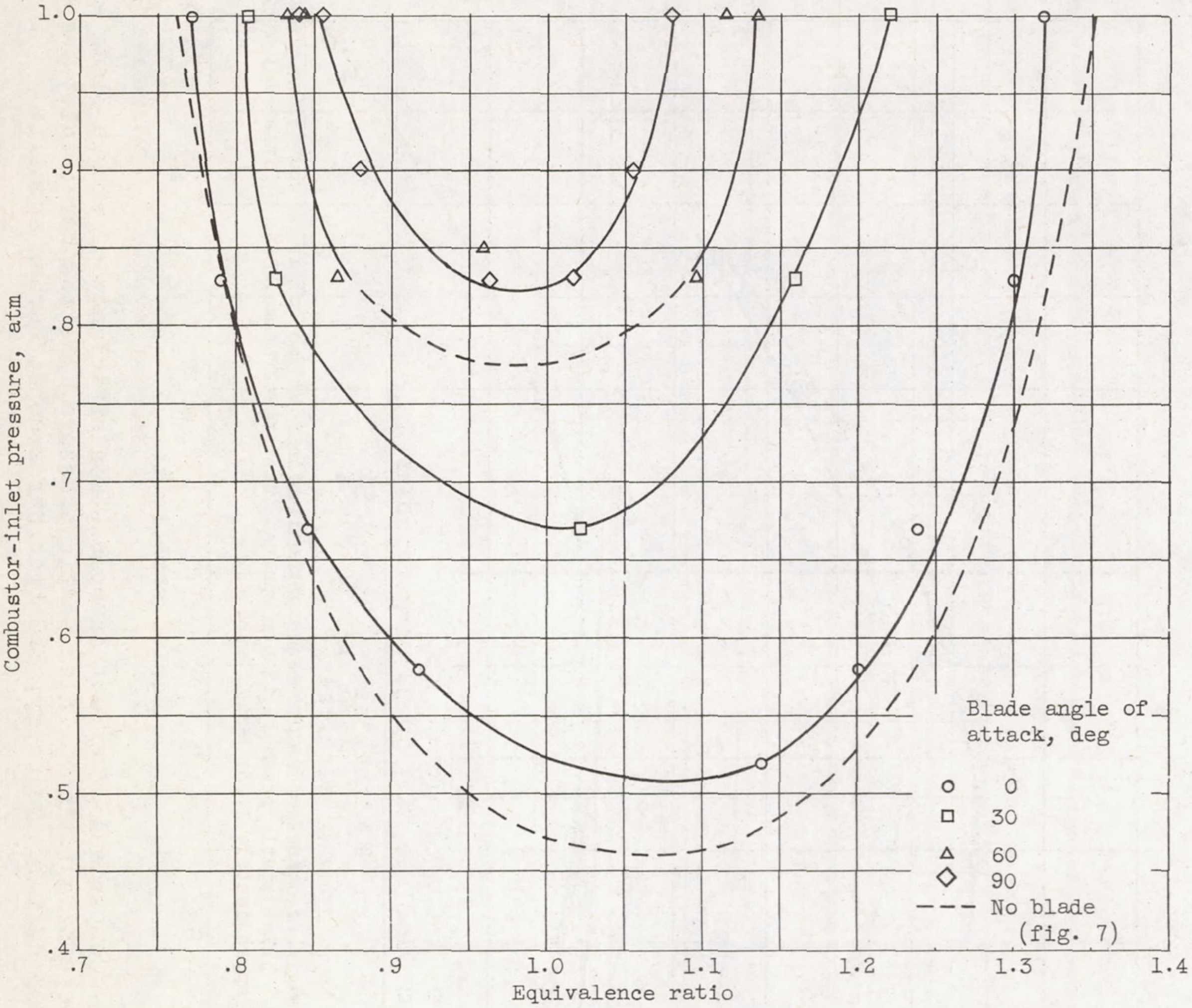


Figure 9. - Effect of blade angle of attack of single blade perpendicular to V-gutter flame holder, 4 inches downstream, on stability limit of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.

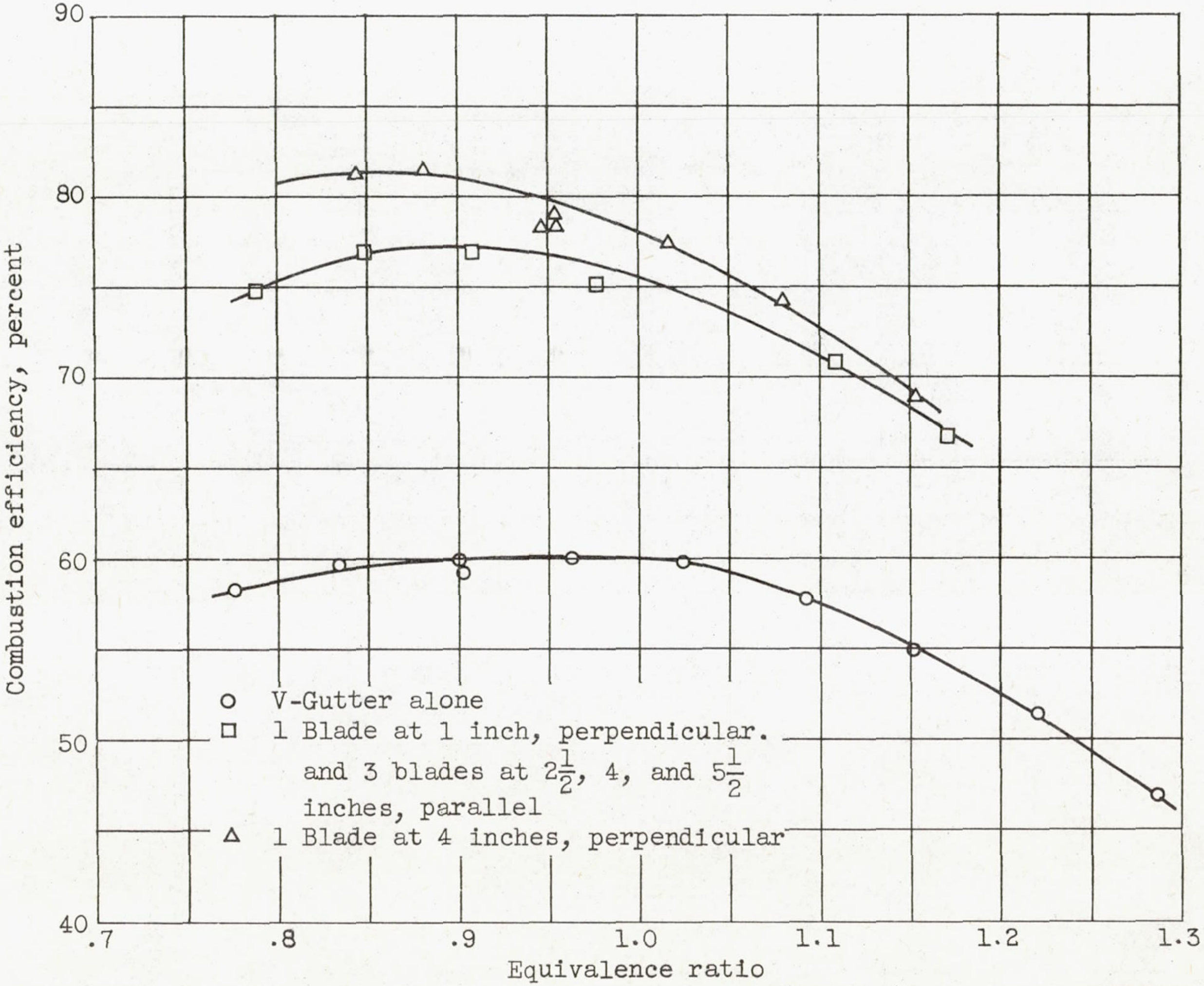


Figure 10. - Comparison of effect on combustion efficiency of single-blade and four-blade configuration. Inlet static pressure, 1 atmosphere; inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.

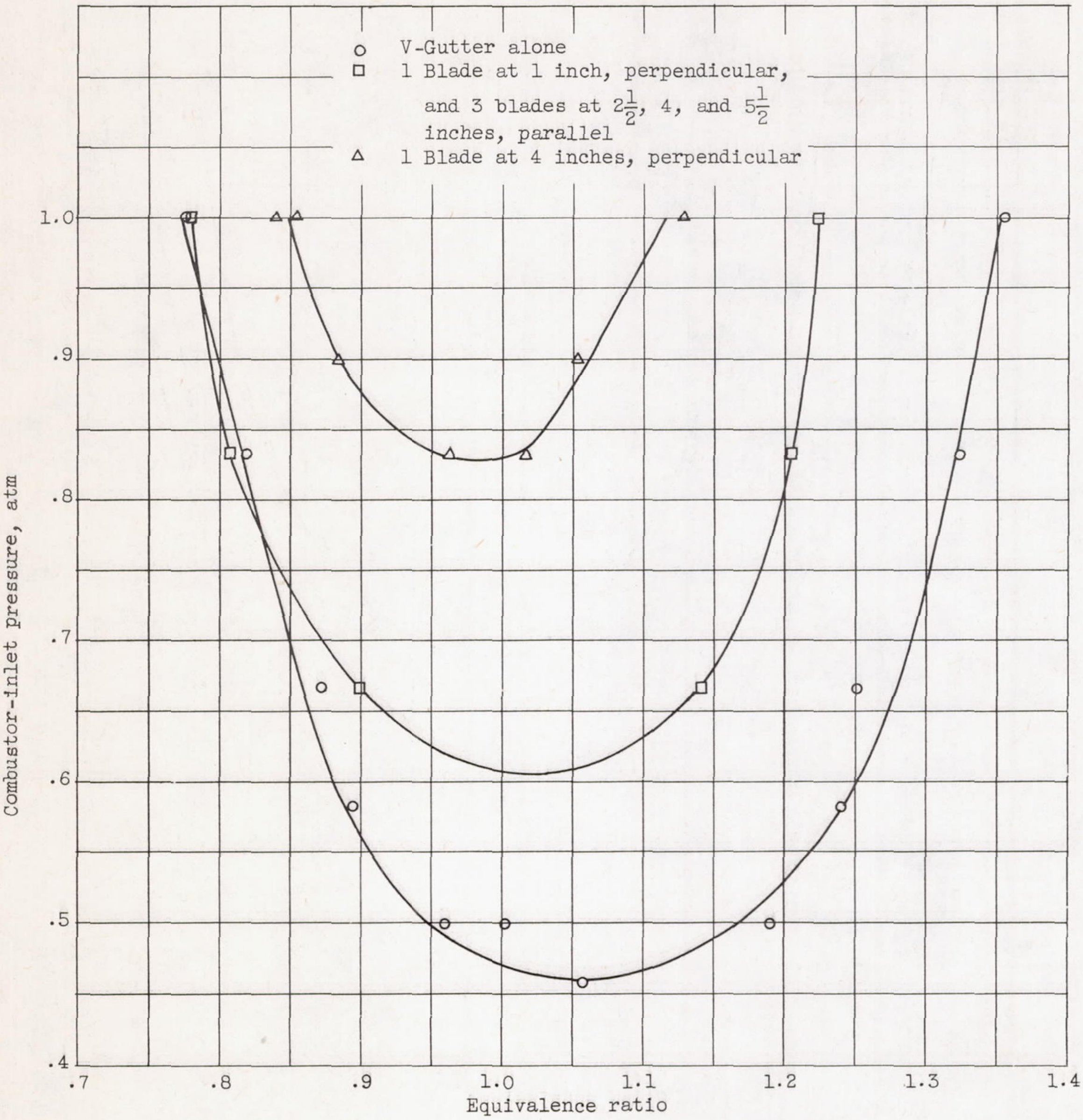
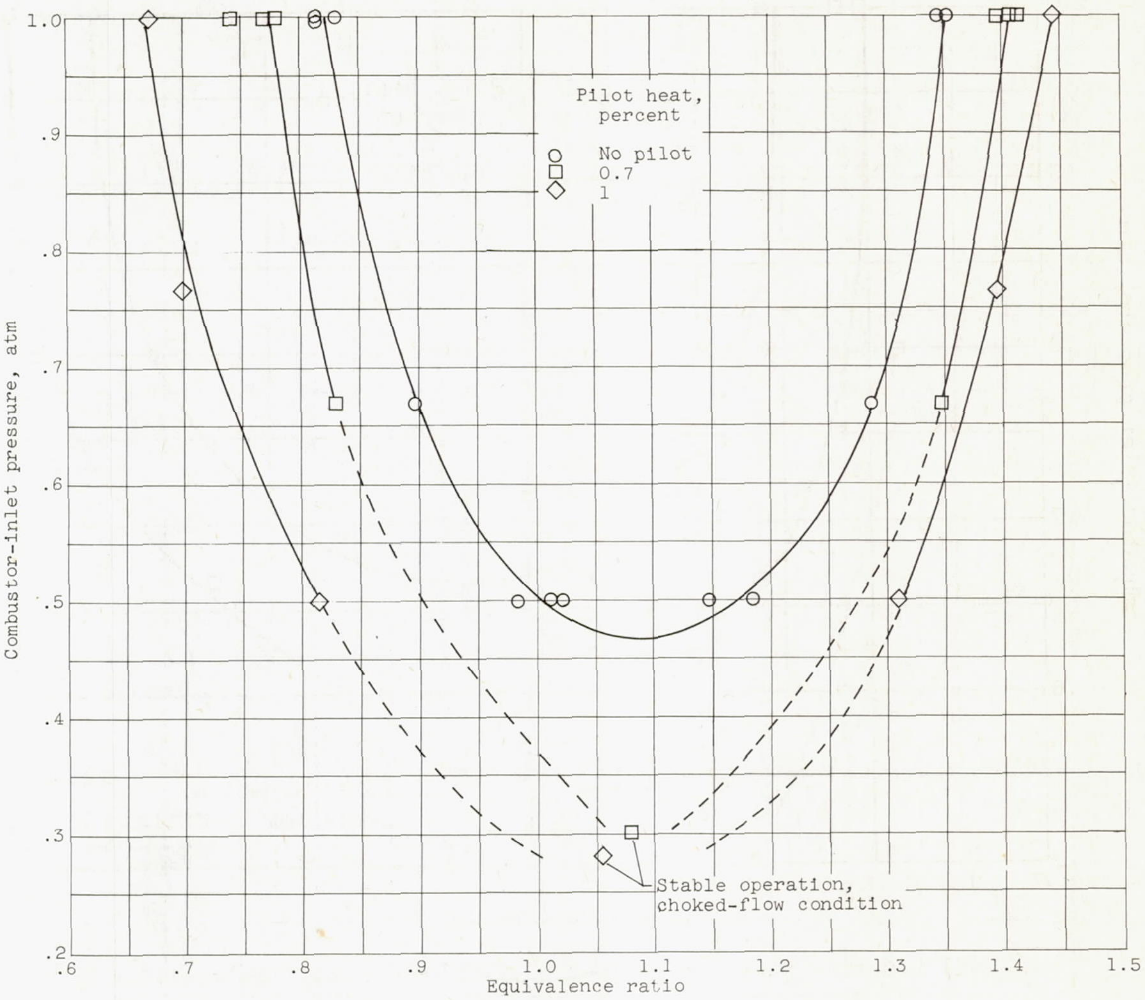
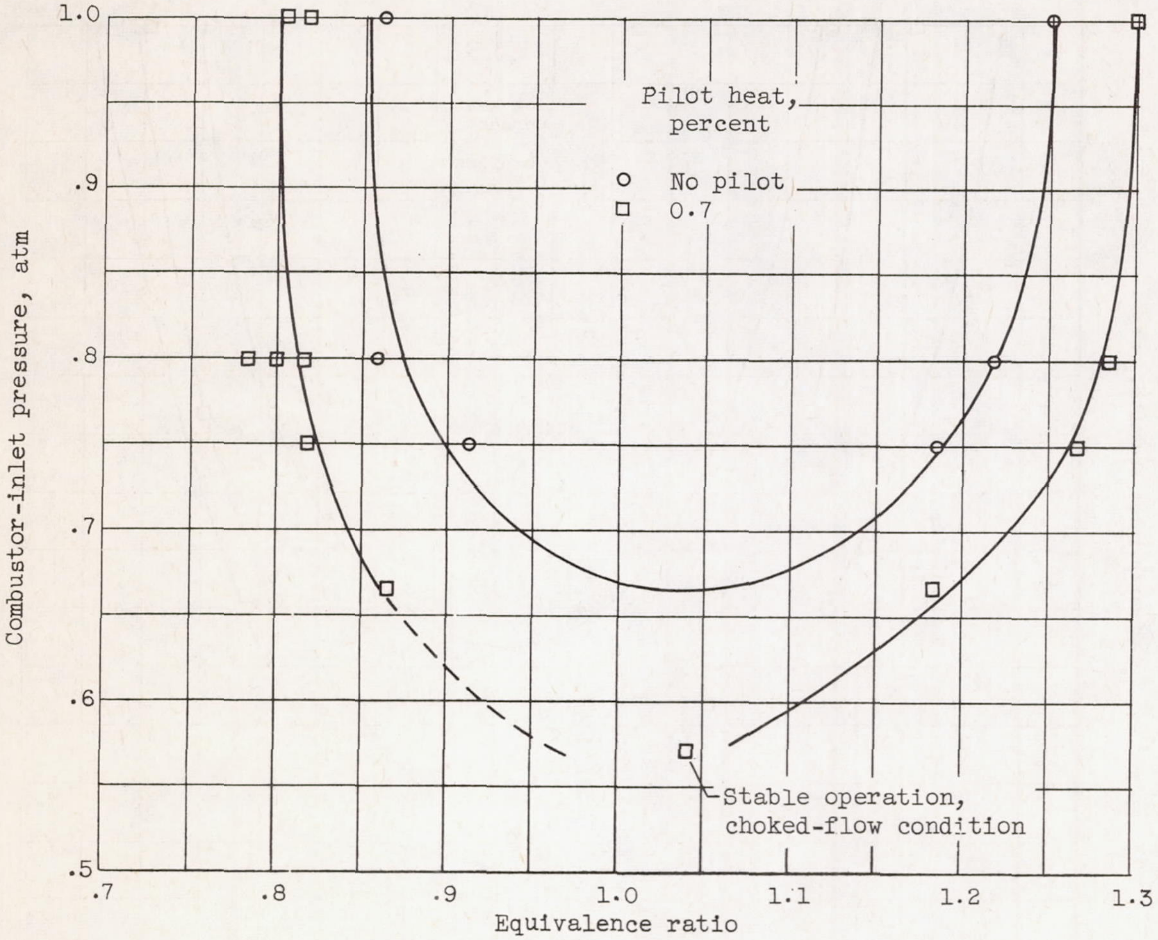


Figure 11. - Comparison of effect on stability limits of single-blade and four-blade configuration. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I.



(a) V-Gutter alone.

Figure 12. - Effect of pilot heat on stability limits of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I. Pilot heat is expressed as percentage of net heating value of fuel at stoichiometric fuel-flow rate.



(b) V-Gutter plus one perpendicular blade at $5\frac{1}{2}$-inch position.

Figure 12. - Concluded. Effect of pilot heat on stability limits of 5-inch-diameter ram-jet combustor. Inlet temperature, 660° R; inlet velocity, 220 feet per second; burner spool I. Pilot heat is expressed as percentage of net heating value of fuel at stoichiomettic fuel-flow rate.