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RESEARCH MEMORANDUM

FULL-SCALE EVALUATION OF SOME FLAMEHOLDER DESIGN CONCEPTS FOR HIGH-INLET-VELOCITY AFTERBURNERS

By William R. Prince, Wallace W. Velie, and Willis M. Braithwaite

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

FULL-SCALE EVALUATION OF SOME FLAMEHOLDER DESIGN CONCEPTS FOR HIGH-INLET-VELOCITY AFTERBURNERS

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SUMMARY

An investigation of a full-scale afterburner having high burner-inlet velocity was conducted at the NACA Lewis laboratory to determine burner performance with several variations in burner design. Variables receiving particular attention were flameholder design and burner length. A total of 12 flameholder configurations, classified by design concept as mixers, screens, or flame spreaders, were investigated at a burner-inlet velocity of 625 feet per second over a range of burner-inlet pressures from 800 to 2700 pounds per square foot absolute.

Data presented indicate that a basic annular two-V-gutter flameholder can operate at combustion efficiencies of 90 to 95 percent for fairly optimum burner length and pressure. A reduction in burner length and burner-inlet pressure had a considerable adverse effect on combustion efficiency of the basic flameholder. Even though the performance of a basic two-V-gutter flameholder was reasonably high at optimum burner conditions, a mixer flameholder configuration showed promise of providing further gains in combustion efficiency, especially at the more critical burner conditions.

INTRODUCTION

Thrust augmentation by means of afterburning extends the range of turbojet engines in the region of supersonic flight speeds. With this advent of higher flight speeds it becomes increasingly important to maintain the frontal area of the propulsion system at a minimum. The transonic compressor, research combustors, and cooled high-stress turbines will probably make use of smaller frontal areas possible. However, with the higher mass flows per unit frontal area obtained for supersonic flight propulsion, satisfactory operation of afterburners at higher inlet velocities will be necessary if the afterburner frontal area and weight are to be kept within limits imposed by the rest of the system.

Whereas present afterburners operate satisfactorily with burner-inlet velocities between 450 and 550 feet per second, it appears that in advanced engines satisfactory afterburner operation will be required at burner-inlet velocities as high as 600 to 650 feet per second. Considerations of design trends of future turbojet engines (ref. 1) and of effects of burner-inlet velocity on momentum pressure drop in the afterburner indicate that a reasonable compromise for burner velocity would be about 625 feet per second. It should be emphasized that the velocity in the combustion zone, because of its effect on burner pressure loss, determines to a great extent the maximum useful afterburner temperature.

To provide information indicating afterburner performance obtainable at high burner-inlet velocities, a program has been conducted at the NACA Lewis laboratory to determine performance with several variations in burner design. Variables receiving particular attention were flameholder design and burner length. A total of 12 flameholder configurations grouped by design concept into three types were investigated at an average burner-inlet velocity of 625 feet per second over a range of burner pressures from 2700 to 800 pounds per square foot absolute at a burner-inlet temperature of about 1700° R. A brief study of performance at a burner-inlet velocity of 500 feet per second, which is representative of present afterburner design practice, was also conducted. The results of the investigation are summarized in this report and show configurations evaluated to provide high combustion efficiency and wide operating limits.

APPARATUS

Installation

The engine-afterburner combination was installed in an altitude test chamber as shown in figure 1. A bulkhead with a labyrinth seal around the front of the engine was used to allow independent control of inlet and exhaust pressures. The laboratory air systems supplied combustion air to the engine and removed the exhaust gases. The engine and afterburner installation was mounted on a thrust platform equipped with a null-type pneumatic balance.

Engine

The investigation was conducted with a production-model axial-flow turbojet engine having a static sea-level military thrust rating of 5970 pounds at an engine speed of 7950 rpm and an exhaust-gas temperature of 1275° F (1735° R).

or (3) flame spreaders. These concepts are based on the following factors which primarily account for the reduction in combustion efficiency at high burner-inlet velocities and low burner pressures:

(1) Reduction in the angle of spread of flame fronts because of increased axial velocity

(2) Poor flame continuity in the gutter piloting zone resulting in an incomplete flame front downstream in the propagating region

(3) Mean reduction in the reaction rate when the combination of high velocity and low pressure are present

The pertinent dimensions and details of the flameholder configurations as well as the purposes of the three designs are given in the following table:

Instrumentation

The location and amount of instrumentation used during this investigation are shown in figure 2. Whirl surveys were taken at a station $14\frac{1}{2}$ inches downstream of the turbine outlet. Fuel-air-ratio surveys were obtained $33\frac{1}{2}$ inches downstream of the turbine outlet $\left(12\frac{1}{2}\right.$ inches downstream of the fuel-spray bars$\left.\right)$. Engine and afterburner fuel flows were measured by calibrated remote-indicating flowmeters. All pressures were measured with manometers and recorded photographically. The temperatures were measured with iron-constantan or chromel-alumel thermocouples; all temperatures were recorded by self-balancing potentiometers.

Afterburner Configurations

Burner. - Figure 3 illustrates the location of the afterburner components and presents the pertinent dimensions and burner details. The diffuser had an area ratio (outlet to inlet) of 1.3 corresponding to an equivalent conical diffuser half-angle of approximately $2\frac{1}{2}^{\circ}$. Antiwhirl vanes were installed at the turbine outlet, and vortex generators were mounted on the diffuser inner body. The burner section was cylindrical and measured 5 feet from diffuser exit to exhaust-nozzle inlet. The first 22 inches of the burner shell was perforated for screech control (ref. 2), and the following 38 inches had a corrugated cooling liner at a mean distance from the outer wall of 1/2 inch. Provision was made for remote axial translation of the flameholder (fig. 4) through a distance of 11 inches, with the forward position $3\frac{1}{2}$ inches downstream of the end of the diffuser inner body. The exhaust nozzle was of the clamshell variable-area type (fig. 5) with an effective maximum diameter of 24 inches as compared to an effective diameter of approximately 19 inches required for nonburning rated engine conditions. Air-cooling was provided for the exhaust nozzle.

Fuel injectors. - One type of fuel injector was used for all configurations (fig. 6). The injectors consisted of flattened radial spray tubes which injected fuel normal to the gas flow. Fuel was injected 21 inches downstream of the turbine outlet. The hole spacing was based on equal mass flow areas. No fuel was injected into approximately 30 percent of the flow area near the outer wall in order to keep fuel out of the burner liner.

Flameholders. - The flameholders used in the investigation were evaluated on the basis of their ability to provide high combustion efficiency at elevated burner velocities. The flameholder configurations are classified according to design concept as (1) mixers, (2) screens,

PROCEDURE

Each flameholder was investigated at the following burner-inlet conditions:

(1) Pressures of 800, 1200, and 2700 pounds per square foot absolute (except where operational problems restricted complete pressure coverage)

(2) Velocity of 625 feet per second (two configurations (1 and 3) were also run at 500 ft/sec)

(3) Turbine-outlet gas temperature of 1700° R

The afterburner fuel-air-ratio range covered was from the value for lean blow-out to the value for limiting turbine-outlet temperature with maximum exhaust-nozzle area. The maximum afterburner fuel-air ratio at maximum exhaust-nozzle area was approximately 0.045 to 0.050, depending upon burner pressure loss and combustion efficiency of the particular configuration. Turbine-inlet hot-streak ignition was used for all configurations.

The engine was operated at rated conditions except for the two runs in which engine speed was reduced to obtain lower burner-inlet velocities. The engine was not operated at any specific flight condition (ram ratio). Engine-inlet pressure was set to maintain the desired burner-inlet pressure, and exhaust pressure was set to maintain a choked exhaust nozzle.

Visual observations of the engine and afterburner outer shell, flameholder, and combustion zone were made during the investigation using observation ports, windows, and a periscope directed toward the flameholder from outside the exhaust nozzle.

Symbols are defined in appendix A and the method of data reduction is presented in appendix B.

RESULTS AND DISCUSSION

Diffuser Performance

Previous afterburner investigations have indicated that for satisfactory afterburner performance the gas flow within the diffuser and into the burner section should have a fairly uniform velocity distribution. Consequently, at the beginning of the program such devices as whirl vanes at the turbine outlet, vortex generators on the diffuser inner body, and a specially shaped diffuser inner cone were incorporated to provide the desired aerodynamic conditions.

FLAMEHOLDER CONFIGURATIONS

Design concept	Configuration	Description	Projected blockage area, percent	Included gutter angle, deg	Gutter width, in.	Mean gutter diam., in.		Translatable	Shown in figure -	Reference	Purpose of design	Remarks
						Inner	Outer					
Reference flameholder	1	Basic two-ring V-gutter	31	30	$1\frac{1}{2}$	9	21	Yes	7	--	--------------	-----------------
Mixer	2	Vortex generator	[a]40	--	--	--	--	No	8(a)	3	Minimize effects of reduced flame-spread angle by mechanical mixing gas downstream of main piloting zone	Used downstream of reference flameholder
	3	Twisted vane	--	--	--	--	--	No	8(b)	--		-----------------
	4	Twisted vane	--	--	--	--	--	No	8(c)	--		Provided additional outboard mixing
Screen	5	Two-ring V-gutter plus 16-mesh[b] screen and 16-mesh overlay	[c]31	30	$1\frac{1}{2}$	9	21	Yes	9(a)	4	Reduce local velocity at gutter	-----------------
	6	Two-ring V-gutter plus 10-mesh[d] screen	[c]31	30	$1\frac{1}{2}$	9	21	Yes	9(b)	--		-----------------
	7	Single-ring V-gutter plus 10-mesh[d] screen	[c]29	30	$1\frac{1}{2}$	--	$17\frac{1}{2}$	Yes	10	--		
Flame spreader	8	Single-ring V-gutter plus 34 small trailing tubes	25	30	2	--	16	Yes	11(a)	4	Minimize effects of reduced flame-spread angle by use of many trailing elements	-----------------
	9	Single-ring V-gutter plus 34 trailing tubes and 34 trailing gutters	31	30	2	--	16	Yes	11(b)	--		-----------------
	10	Single-ring V-gutter plus 68 small trailing tubes	31	30	2	--	16	Yes	11(c)	--		-----------------
	11	Single-ring V-gutter with no trailing elements	31	30	$3\frac{1}{2}$	--	16	Yes	11(d)	--		Same blockage as configuration 10
	12	Single-ring V-gutter plus large trailing elements	29	30	$1\frac{1}{2}$	--	$17\frac{1}{2}$	Yes	10(b)	--		-----------------

[a]Including mixer.
[b]0.020-In.-diam. wire, 46.2 percent open area.
[c]Excluding screens.
[d]0.025-In.-diam. wire, 56.3 percent open area.

burner pressure. Burner pressure loss (from burner inlet to exhaust-nozzle inlet) had a peak value of about 12 percent for all burner pressures. Nonburning burner pressure loss was about 5 percent, not including the diffuser pressure loss which was approximately 2.5 percent. These pressure losses for a conventional flameholder are higher than present practice because of the higher burner velocity.

Effect of burner-inlet velocity. - The effect of burner velocity on performance of the reference flameholder is presented in figure 17 for a burner length of 51 inches and a burner-inlet pressure of 800 pounds per square foot absolute. The results show that increasing burner-inlet velocity from 500 to 625 feet per second lowered combustion efficiency 3 to 4 percentage points. These results, in general, agree with results shown for the effect of increased burner velocity as presented in reference 5 for comparable conditions. In addition to the effect of increased velocity on combustion efficiency, there is also the effect of increased velocity on burner pressure loss. This amounted to an increase in peak burner pressure loss of about 40 percent for the increase in velocity from 500 to 625 feet per second. This increase in burner pressure loss would be reflected in a lower augmented thrust for a given exhaust-gas temperature.

Effect of burner length and inlet conditions. - The effect of burner length, burner-inlet pressure, and burner-inlet velocity on burner performance is summarized in figure 18. Reducing burner length from 57 to 46 inches (fig. 18(a)) lowered combustion efficiency from about 80 to 65 percent at a pressure of 800 pounds per square foot absolute. The effect of burner length on combustion efficiency was less as burner pressure was increased.

Burner pressure loss was 1 to 2 percentage points higher for the longer burner lengths. The more efficient burner resulted in slightly higher momentum pressure loss because of increased gas temperature; also, the proximity of the flameholder to the diffuser may have resulted in higher friction pressure loss because of the flameholder being in a region of higher local velocity when in the forward position (maximum burner length).

A decrease in burner pressure (fig. 18(b)) from 2700 to 800 pounds per square foot absolute reduced combustion efficiency from about 95 to 80 percent. The trend of the curve indicated that any further decrease in burner pressure would be accompanied by considerable efficiency reduction.

Raising burner-inlet velocity (fig. 18(c)) from 500 to 625 feet per second reduced efficiency only a small amount, but, as discussed earlier, increased burner pressure loss appreciably.

The rate of diffusion for the afterburner diffuser used in this investigation is shown in figure 12, which presents area ratio against diffuser length. The photograph shows the diffuser inner body and the vortex generators.

Antiwhirl vanes were installed at the turbine outlet (fig. 13) to minimize the angle of whirl of the gas flow within the diffuser. The resulting whirl characteristics are presented in figure 13, which shows whirl angle as a function of passage height for various engine operating conditions. The maximum whirl angle was approximately 10° to 12° and was not affected by variation in either burner-inlet velocity or pressure.

Fairly uniform diffuser-outlet velocity distribtuions (V_{local}/V_{max} of 80 to 85 percent) were obtained for representative burner-inlet conditions (fig. 14). The velocity profile was not appreciably affected by change in burner-inlet pressure or velocity.

The effect of burner-inlet pressure on fuel-air-ratio variation at the diffuser outlet is presented in figure 15. The fuel-air-ratio plots are superimposed on a scale outline of the afterburner to show the positions of fuel-spray bars and the flameholder relative to the fuel-air-ratio survey station. The outer 30 percent of the annulus was operating at approximately engine fuel-air ratio to maintain the burner shell at safe operating temperature. A more uniform fuel-air ratio is indicated with increase in burner pressure and attendant higher fuel-manifold pressure.

Performance of Reference Two-V-Gutter Flameholder

To provide a basis for comparison of burner modifications, the performance characteristics of a conventional two-V-gutter flameholder are presented first.

Effect of burner pressure. - Pressure has a considerable effect on the efficiency of the combustion process. The effect of changes in burner-inlet pressure from 2700 to 800 pounds per square foot absolute on afterburner performance at a burner-inlet velocity of 625 feet per second is shown in figure 16 for a fixed burner length of 57 inches. Burner length is defined as the distance from the leading edge of the main flameholder gutter to the exhaust-nozzle inlet. Throughout the investigation, variation in burner length was achieved by translation of the flameholder. Efficiency, in general, was only slightly affected by the limited variation in fuel-air ratio. Peak combustion efficiencies of 95, 90, and 82 percent occurred at a fuel-air ratio of 0.0425 for burner pressures of 2700, 1200, and 800 pounds per square foot absolute, respectively. The lean blowout, as expected, improved with increased

In general, it can be concluded that with the best mixer closely coupled to the flameholder, combustion efficiency increases of as much as 0.13 were obtained with an increase in burner pressure loss of 0.010 to 0.015.

Screens. - The application of several screen configurations to annular V-gutter elements and the effect on burner performance are shown in figure 22 for two burner lengths. For the 51-inch burner length, the addition of a 16-mesh screen plus a 16-mesh overlay screen to the reference flameholder resulted in about an 80-percent increase in burner pressure loss at a fuel-air ratio of 0.035 with no improvement in efficiency. This increase in burner pressure loss was approximately cut in half by using a 10-mesh screen and making the capture area less than the gutter width. With this screen configuration, the lean operating fuel-air-ratio limits of the reference flameholder were improved by as much as 0.005. The range of operation of the reference two-V-gutter flameholder with the screen additions was restricted because of the combination of high burner pressure loss and limited exhaust-nozzle area. A less severe screen addition to a single-V-gutter flameholder resulted in only about a 20-percent increase in pressure loss when compared to operation with no screens. Combustion efficiency was poorer than with the reference two-V-gutter flameholder but was about 5 percentage points higher with screens than without. Lean stability limits again were improved by the addition of the screens.

From this investigation, the screen technique does not appear promising, because the small gain in combustion efficiency is offset (from the standpoint of thrust and specific fuel consumption) by the greater burner pressure loss.

Flame spreaders. - The flame-spreading technique, as mentioned earlier, was used to minimize the reduced flame-spread angle resulting from higher burner velocity by the use of many trailing elements. Performance of a relatively large single-V-gutter flameholder coupled with various trailing-finger-gutter configurations is presented in figure 23 for three burner lengths. The combustion efficiencies for all the configurations were less than for the reference two-V-gutter flameholders. Because of superior lean limits, the operating range was greater than that for the reference flameholder. In general, the burner pressure loss for all configurations was comparable to that of the reference flameholder. In order to determine the best trailing-element configuration (open gutter, solid bar, different diameter tubes, etc.), visual inspection of a special flameholder shown in figure 24 was made during burning. The 1/4-inch tube configuration proved to have superior flameholding ability. An increase in the number of tubes, however, resulted in no improvement in efficiency. Although flame was seated on the spreaders, there may not have been strong enough pilot sources to produce propagation burning. To further illustrate the flame-spreading principle, all

Designs to Improve Combustion for High-Velocity Conditions

Mixers. - As is previously mentioned, the purpose of the mixer was to minimize the effect of reduced flame spread angle by increasing the mixing of burned and unburned mixture downstream of the flameholder gutter zone and in so doing improve combustion efficiency. The variation of burner performance with fuel-air ratio at a burner pressure of 1200 pounds per square foot absolute by the installation of several mixer configurations downstream of the reference flameholder is presented in figure 19. The performance of the individual mixer configurations for different burner lengths is compared with the performance of the reference flameholder without mixer addition (shown by dotted line). The mixer configurations were fixed to the burner outer wall and the flameholder was translated to produce the different spacing between the mixer and the gutter and also the different burner lengths.

In general, for the same spacing between gutter and mixer, the vortex-generator mixer was superior to the twisted-vane type. For example, the combustion efficiency for the vortex type was 2 to 5 percentage points higher, and burner pressure loss was about 0.005 (4 percent) less than with the twisted-vane type. All mixer configurations, except those with extreme spacing between gutter and mixer, improved the efficiency of the reference flameholder. For the short (46-inch) burner the addition of a vortex-generator mixer resulted in an increase of as much as 0.13 in combustion efficiency. An attempt to increase the mixing by the addition of a twisted-vane mixer outboard of the original mixer (fig. 8(c)) was not effective in further improving efficiency. This was probably due to the ineffectual lean zone near the outer wall (fuel-air-ratio survey station, fig. 15) where mixing resulted, to some extent, in quenching in the main burning zone. The flame stability of the reference flameholder was not significantly improved by the mixer addition. The addition of the mixers raised the burner pressure loss 0.01 to 0.02.

The effect of the spacing between the gutter and mixer on burner performance is shown in figure 20 for two burner pressures. Close coupling of the mixer to the main burning zone (gutter) improved combustion efficiency by 12 to 13 percentage points, whereas spacing the mixer 13 inches downstream of the gutter resulted in only 1-point improvement. The results were similar for burner-inlet pressures of 800 and 1200 pounds per square foot absolute. The extreme downstream location of the mixer also proved undesirable from the standpoint of mixer life; damage to the mixer elements of the twisted-vane mixer located 19 inches from the flameholder gutter resulted after only short operation (fig. 21). Burner pressure loss was not affected by changes in distance between mixer and gutter.

of the fingers were removed and the main gutter width was increased to hold the blockage constant. The result was that the efficiency was approximately the same as that for the best finger configuration.

The conclusion can be made that the flame spreaders investigated herein do not hold much promise of improving combustion efficiency over that obtainable with a basic annular two-V-gutter flameholder.

A performance summary of the optimum flameholder configuration from each design group is shown in the bar graph (fig. 25) for a burner length of 46 inches and burner-inlet velocity of 625 feet per second. The vortex-generator mixer flameholder was the most promising; it showed combustion efficiency gains over the reference flameholder of as much as 0.13 with an increase of only about 0.01 in burner pressure loss.

Operational Characteristics

<u>Lean stability</u>. - Evaluation of the lean stability limits of all the flameholder configurations over a range of burner-inlet pressures is shown in a bar graph (fig. 26) for a burner length of 51 inches. A decrease in burner pressure showed the expected reduction in stability limits for all the configurations. The application of mixers to the reference flameholder did not appreciably change its stability limits. The use of screen additions, preferably those resulting in small increases in pressure loss, improved lean blow-out fuel-air ratio by as much as 0.01. A limited number of trailing finger elements (34) attached to a main annular gutter indicate as much improvement in lean-limit fuel-air ratio as 0.007 over that for the reference flameholder.

The effect of burner length and burner-inlet velocity on lean blow-out characteristics of several flameholder configurations is presented in figure 27. The greater burning length resulted in the best stability limits for all configurations. The maximum effect of burner length was shown for the screen additions to the reference flameholder. Lean blow-out was only slightly improved by reduction in burner-inlet velocity from 625 to 500 feet per second.

<u>General</u>. - Successful ignition of the afterburner was accomplished for the entire investigation by use of a preturbine hot-streak method. The combustion process was free of screech for all configurations investigated. A ceramic coated 0.060-inch Inconel liner was in good condition at the end of the investigation after more than 50 hours of operation.

CONCLUDING REMARKS

The results presented herein for a burner having an inlet velocity of 625 feet per second indicate that a basic annular two-V-gutter flameholder with blockage of about 30 percent is capable of operating at combustion efficiencies of 90 to 95 percent for optimum burner conditions, that is, a burner length of 5 feet and burner pressure of at least 1200 pounds per square foot absolute. A reduction in burner length of about 1 foot lowered the efficiency to 80 percent. Maintaining the minimum burner length and reducing burner-inlet pressure from 1200 to 800 pounds per square foot absolute further reduced efficiency to about 65 percent. These values demonstrate the considerable adverse effect on combustion efficiency of reduction in burner length for a burner having high inlet velocity. Even though combustion efficiency was reasonably high for the annular two-V-gutter flameholder at optimum burner conditions, some flameholder configurations showed promise of providing further gains in efficiency, especially at the more critical burner conditions. By far the most promising configuration was the mixer. The best mixer was the vortex-generator type which showed combustion efficiency gains over the basic two-V-gutter flameholder of as much as 0.13 with an increase of only about 0.01 in burner pressure loss. The screen and flame-spreader configurations showed little, if any, promise for improving combustion efficiency. The lean operating fuel-air-ratio limits, however, for the screen and flame-spreader configurations as compared with those for the basic two-V-gutter flameholder were improved by as much as 0.007 to 0.010. The flame stability of the basic two-V-gutter flameholder was not significantly improved by the addition of the mixer.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 16, 1956

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A cross-sectional area, sq ft

C_V effective velocity coefficient, ratio of scale jet thrust to ideal jet thrust

$F_{j,s}$ scale jet thrust, lb

f fuel-air ratio

g acceleration due to gravity, 32.2 ft/sec^2

P total pressure, lb/sq ft

R universal gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)

T total temperature, $^{\circ}$R

V velocity, ft/sec

w weight flow, lb/sec

γ ratio of specific heats

η combustion efficiency

Subscripts:

a air

ab afterburner

e engine

eff effective

f fuel

g gas

i ideal

m	midframe vent
stoic	stoichiometric
t	total
2	engine inlet
7	diffuser outlet
8	exhaust-nozzle inlet

APPENDIX B

METHODS OF CALCULATION

The engine inlet and minor air flows are calculated by means of the one-dimensional flow parameters derived in reference 6. The equation is:

$$w_a = \left(\frac{M\sqrt{gRT}}{PA}\right)\frac{PA}{\sqrt{R/g}\sqrt{T}}$$

where

$\frac{M\sqrt{gRT}}{PA}$ is the reciprocal of the total-pressure parameter and is a function of the static- to total-pressure ratio and of the ratio of specific heats $(\gamma = 1.4)$, and A is the calibrated area of the measuring station.

The tailpipe air flow obtained by reducing the engine-inlet air flow by the amount bled overboard is $w_{a,8} = w_{a,2} - w_{a,m}$.

The fuel-air ratios are obtained as follows:

Engine

$$f_e = \frac{w_{f,e}}{3600\ w_{a,8}}$$

Total

$$f_t = \frac{w_{f,e} + w_{f,ab}}{3600\ w_{a,8}}$$

Afterburner

$$f_{ab} = \frac{f_t - f_{e,i}}{1 - \frac{f_{e,i}}{f_{stoic}}}$$

where $f_{e,i}$ is the fuel-air ratio required to give the temperature rise across the engine at 100-percent combustion efficiency (ref. 5), and f_{stoic} is the stoichiometric fuel-air ratio for the fuel, 0.0676.

The afterburner-exit temperature is calculated from the measured jet thrust by the equation

$$T_8 = \left[\frac{F_{j,s}}{w_{g,8}} \frac{\sqrt{g/R}}{(V_{eff}/\sqrt{gRT})C_V}\right]^2$$

where $w_{g,8} = w_{a,8}(1 + f_t)$; $\dfrac{V_{eff}}{\sqrt{gRT}}$ is the velocity parameter obtained from reference 7; $C_V = \dfrac{F_{j,s}}{w_{g,8} \dfrac{V_{eff}}{\sqrt{gRT}} \sqrt{R/g} \sqrt{T_8}}$ as obtained for the given exhaust nozzle from data for nonburning conditions.

The afterburner combustion efficiency is defined as the ratio of the fuel-air ratio ideally required to give the temperature rise from the turbine outlet to the afterburner exit to the measured afterburner fuel-air ratio and may be written

$$\eta_{ab} = \frac{f_{ab,i}}{f_{ab}}$$

where $f_{ab,i} = \dfrac{f_{t,i} - f_{e,i}}{1 - \dfrac{f_{e,i}}{f_{stoic}}}$, and $f_{t,i}$ is obtained from the temperature rise $T_8 - T_2$ as in reference 5.

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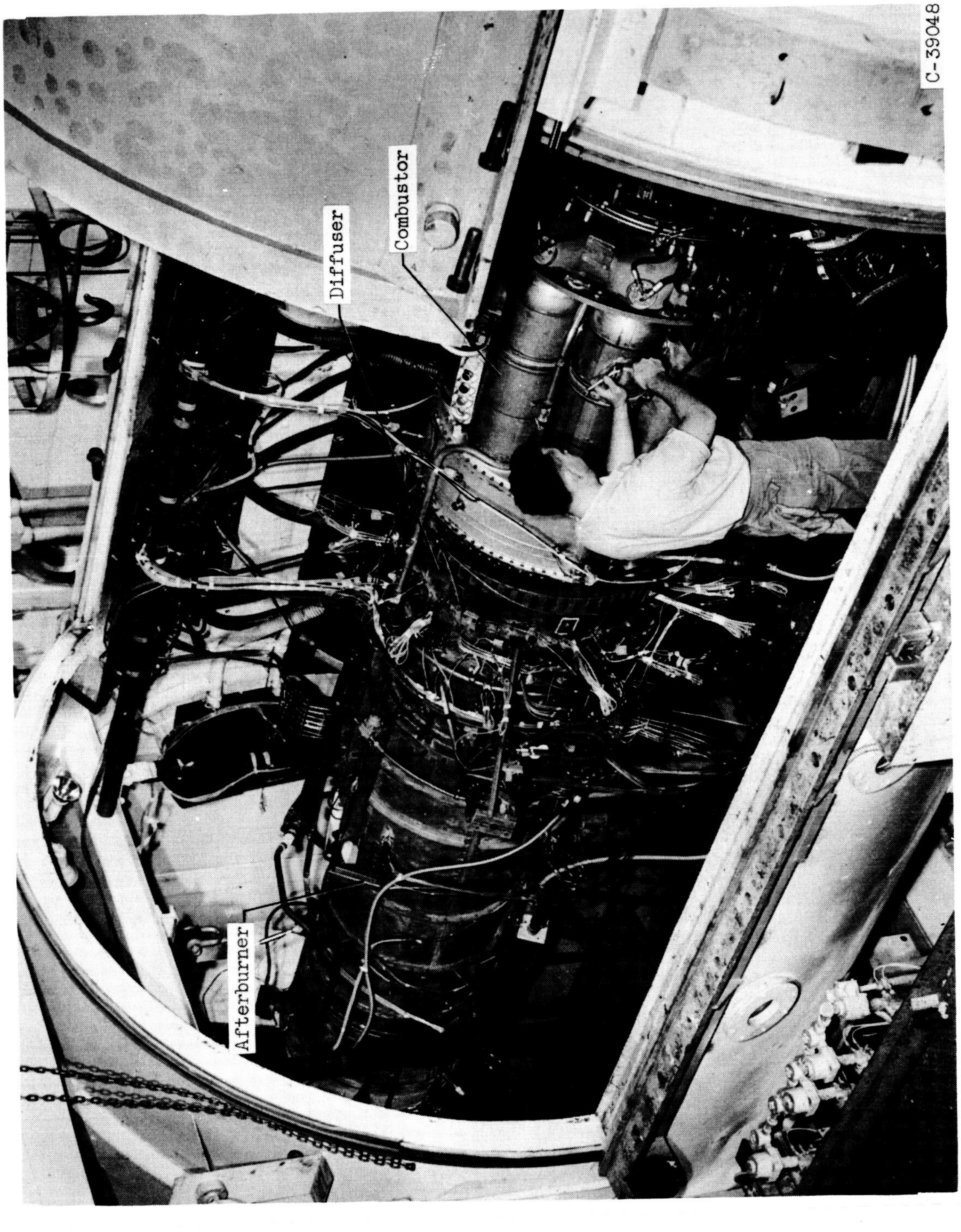
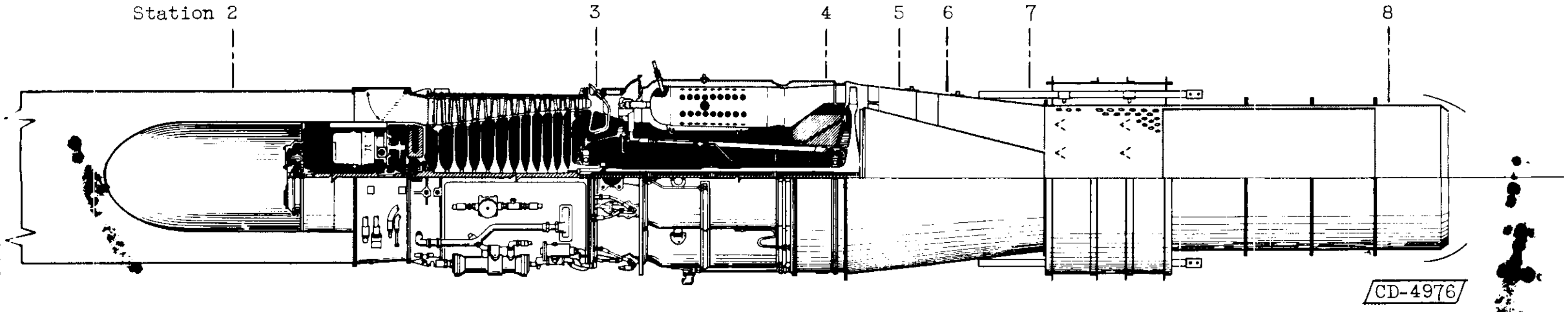


Figure 1. - Engine and afterburner installation in altitude test chamber.



Station	Total-pressure tubes	Static-pressure tubes	Wall static-pressure orifices	Thermo-couples
2	24	6	4	8
3	6	-	-	6
4	4	-	-	8
5	12	-	2	30
6	12	-	4	16
7	32	8	8	8
8	13	-	2	-

Figure 2. - Location and amount of instrumentation.

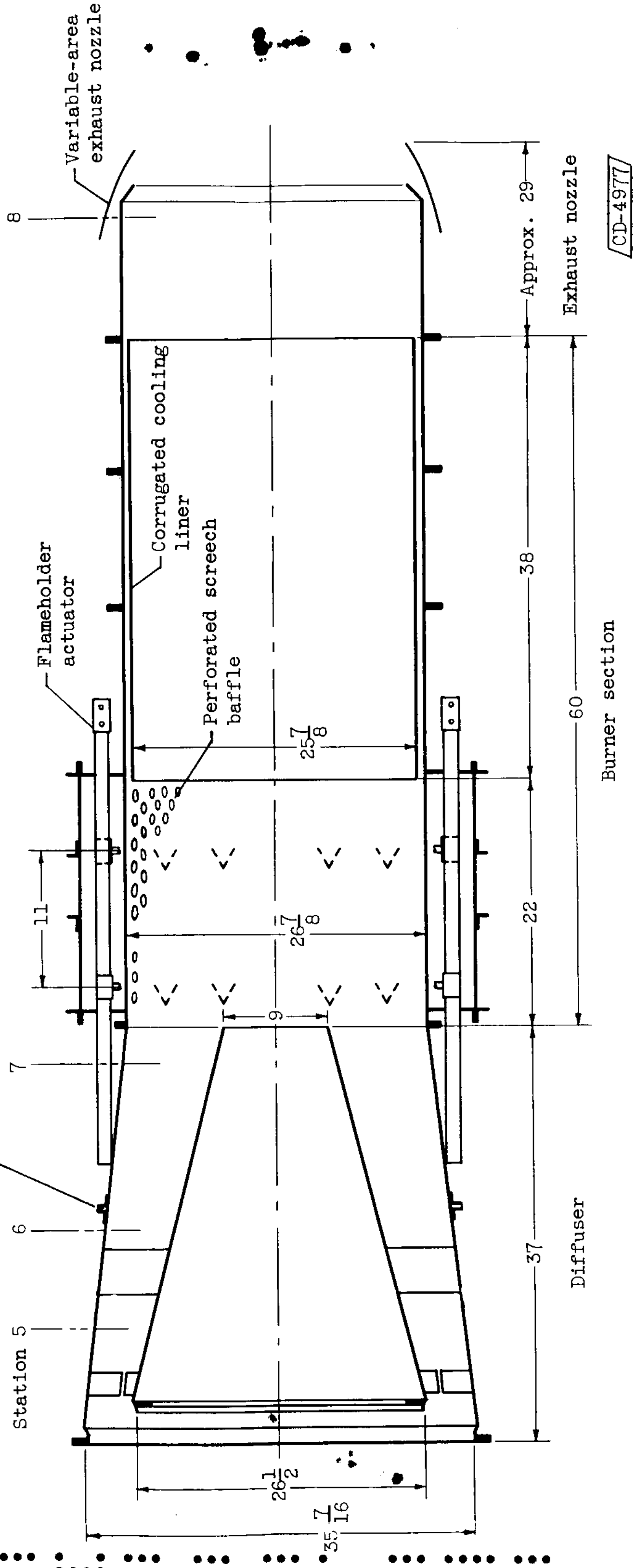


Figure 3. - Details of afterburner. (All dimensions in inches.)

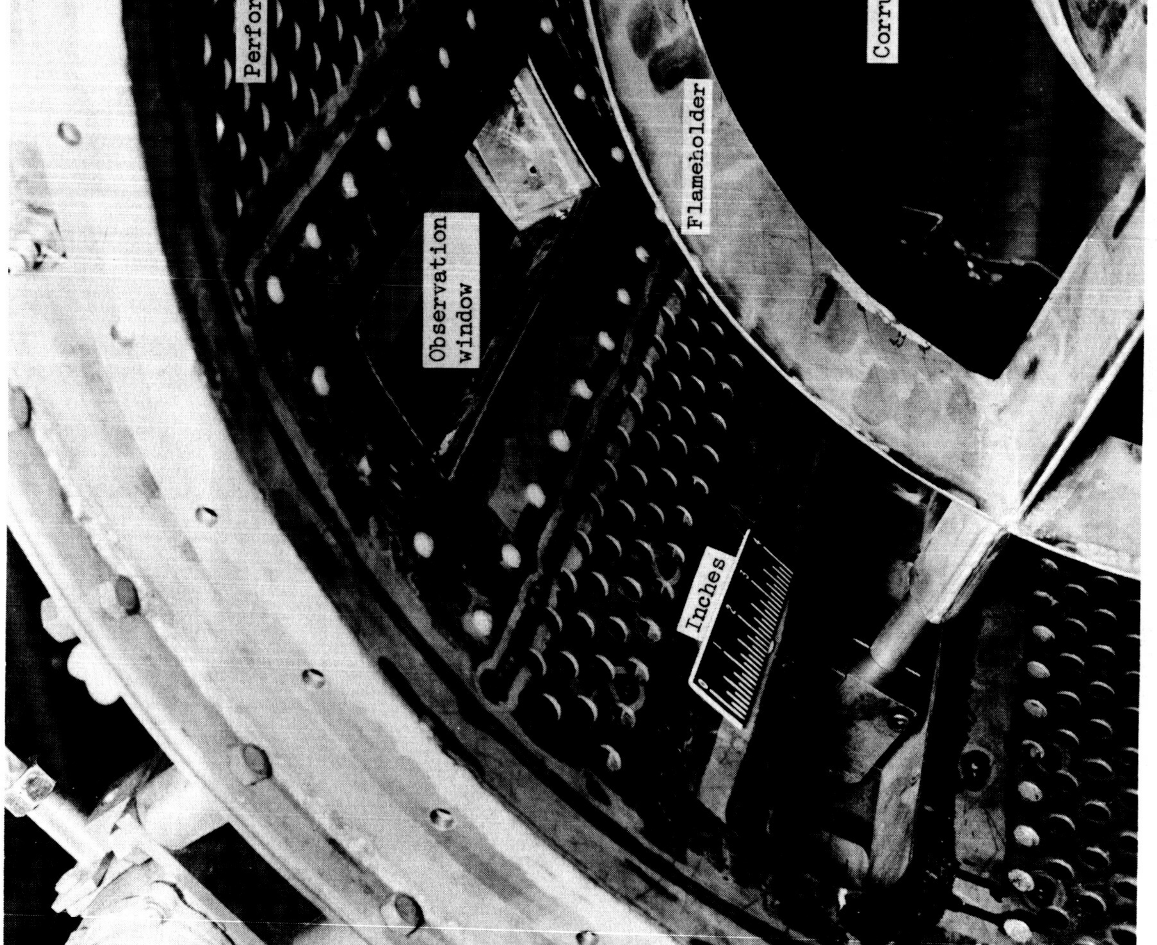


Figure 4. - Photograph showing flameholder translating arrangement (looking downstream).

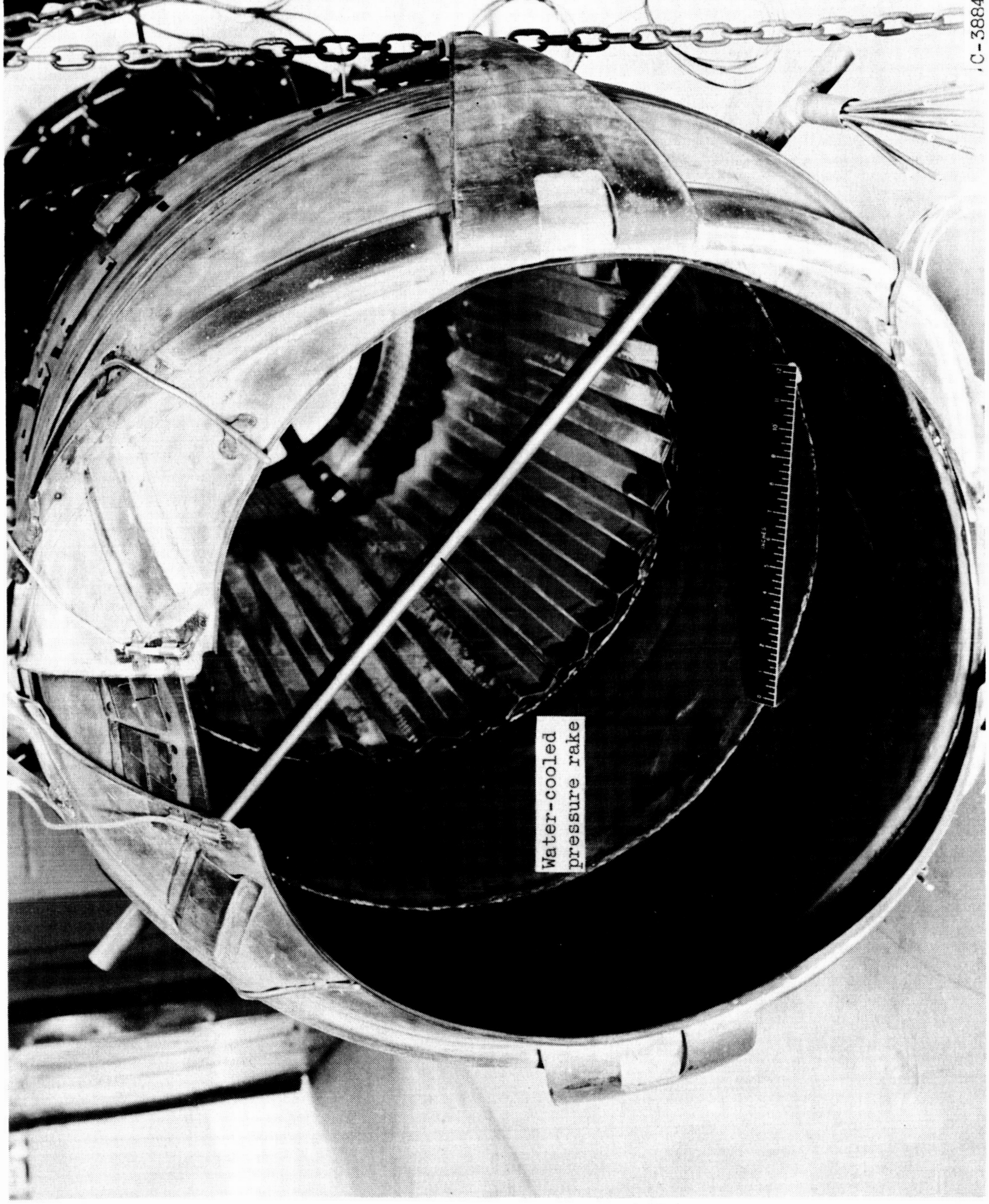
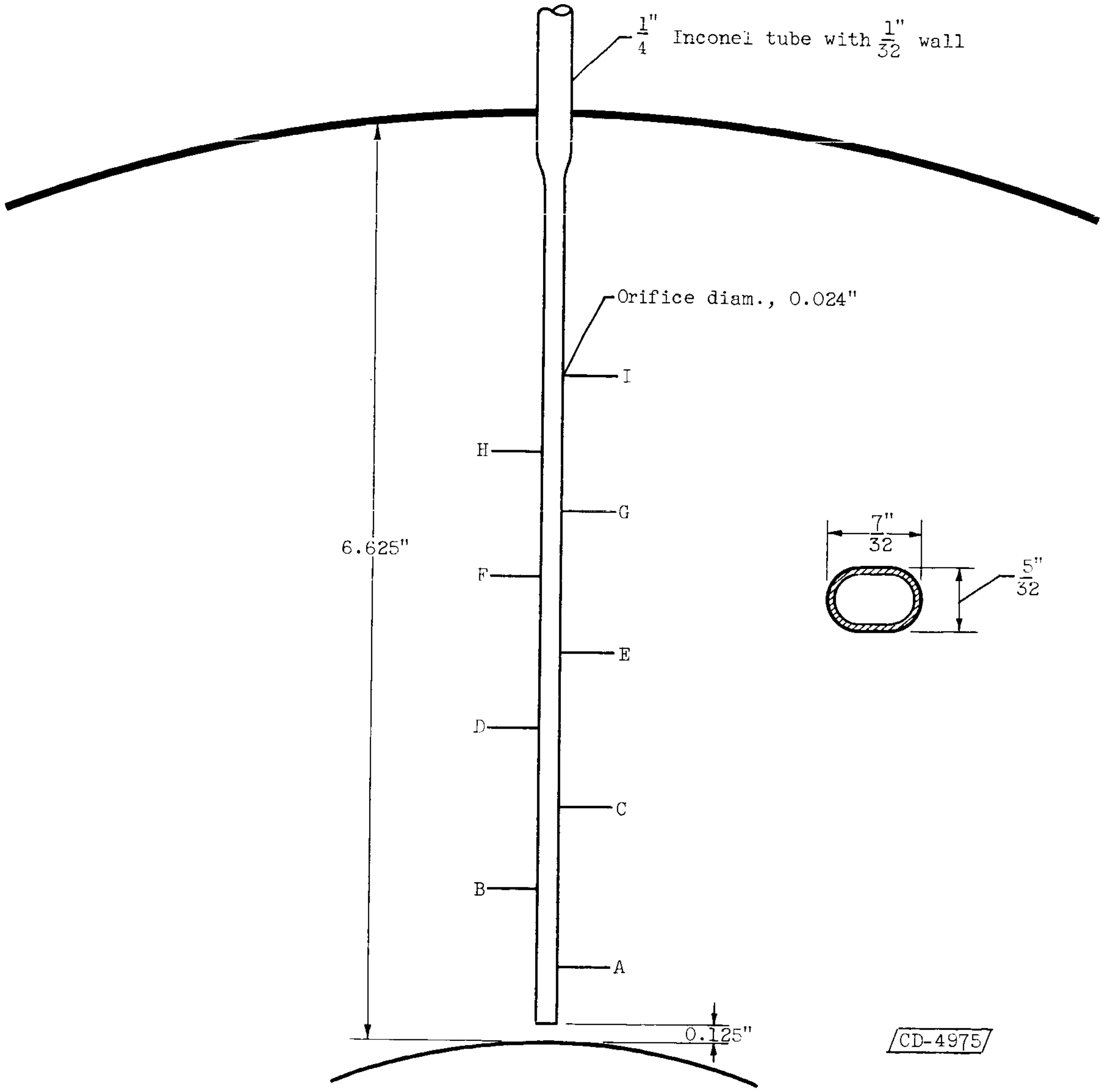


Figure 5. - Photograph showing variable-area exhaust nozzle and water-cooled pressure rake (looking upstream).



Fuel orifice	A	B	C	D	E	F	G	H	I
Distance from end of bar, in.	0.4	0.95	1.54	2.10	2.65	3.19	3.65	4.08	4.62

Figure 6. - Fuel injector tube (24 injectors in engine).

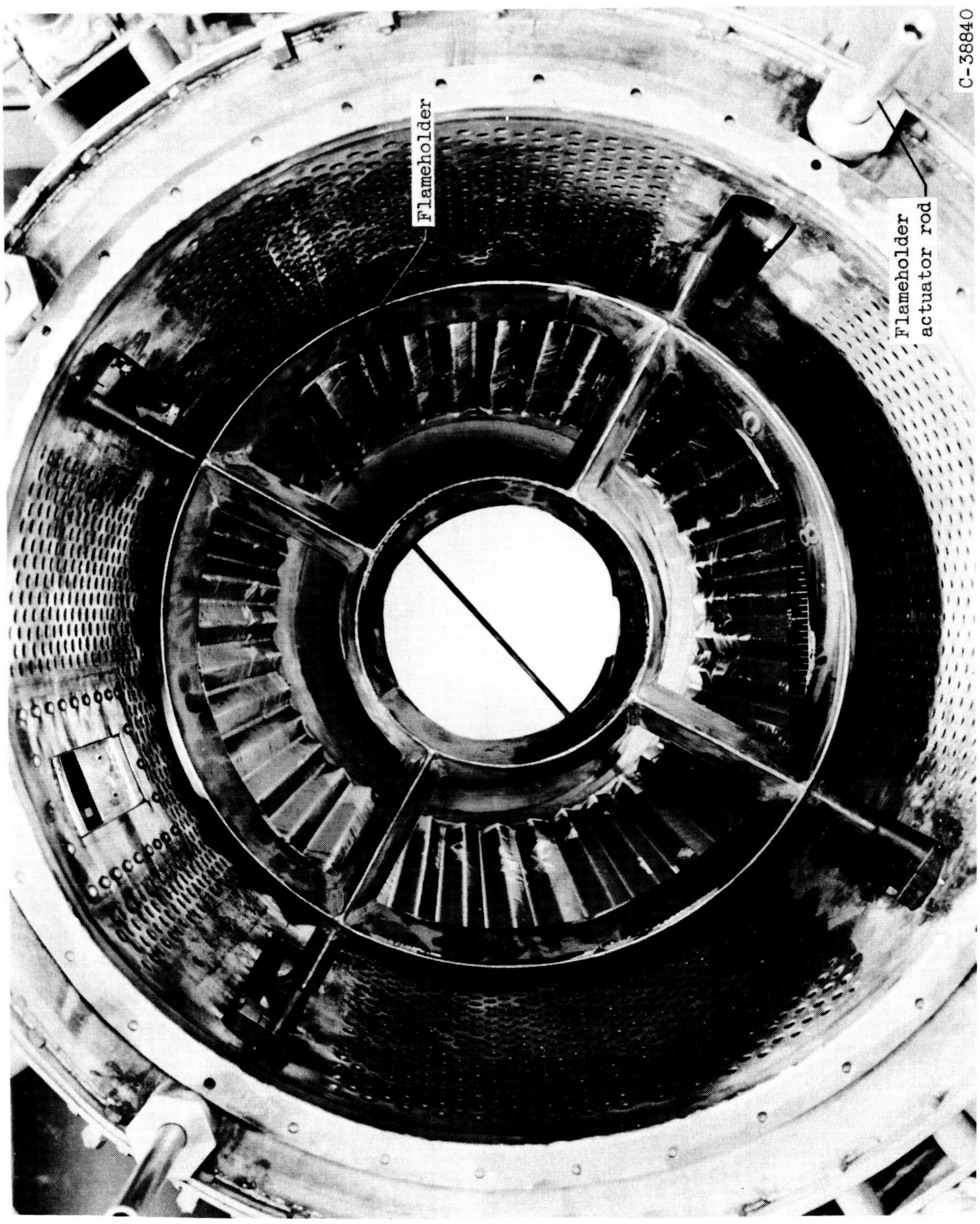
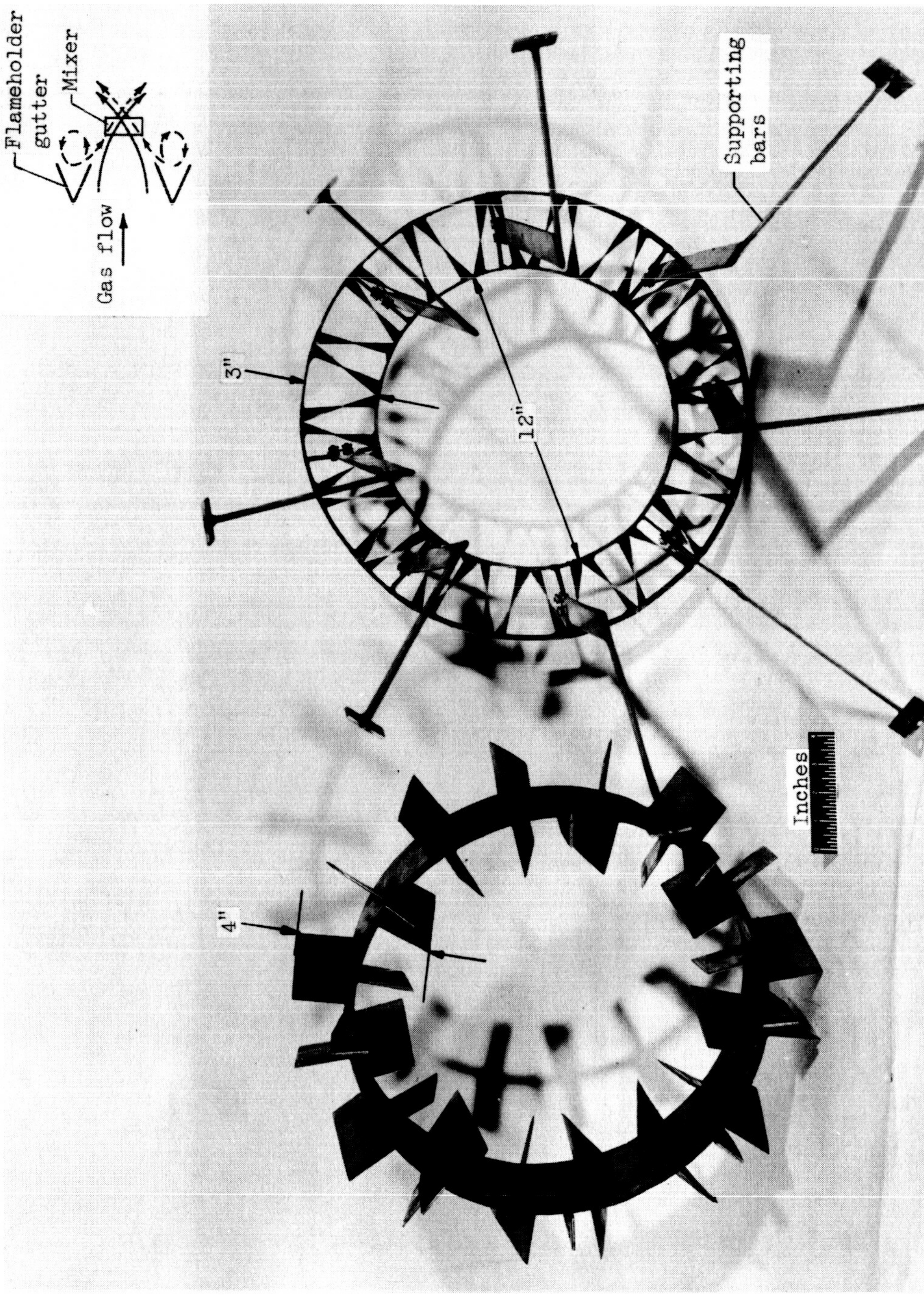


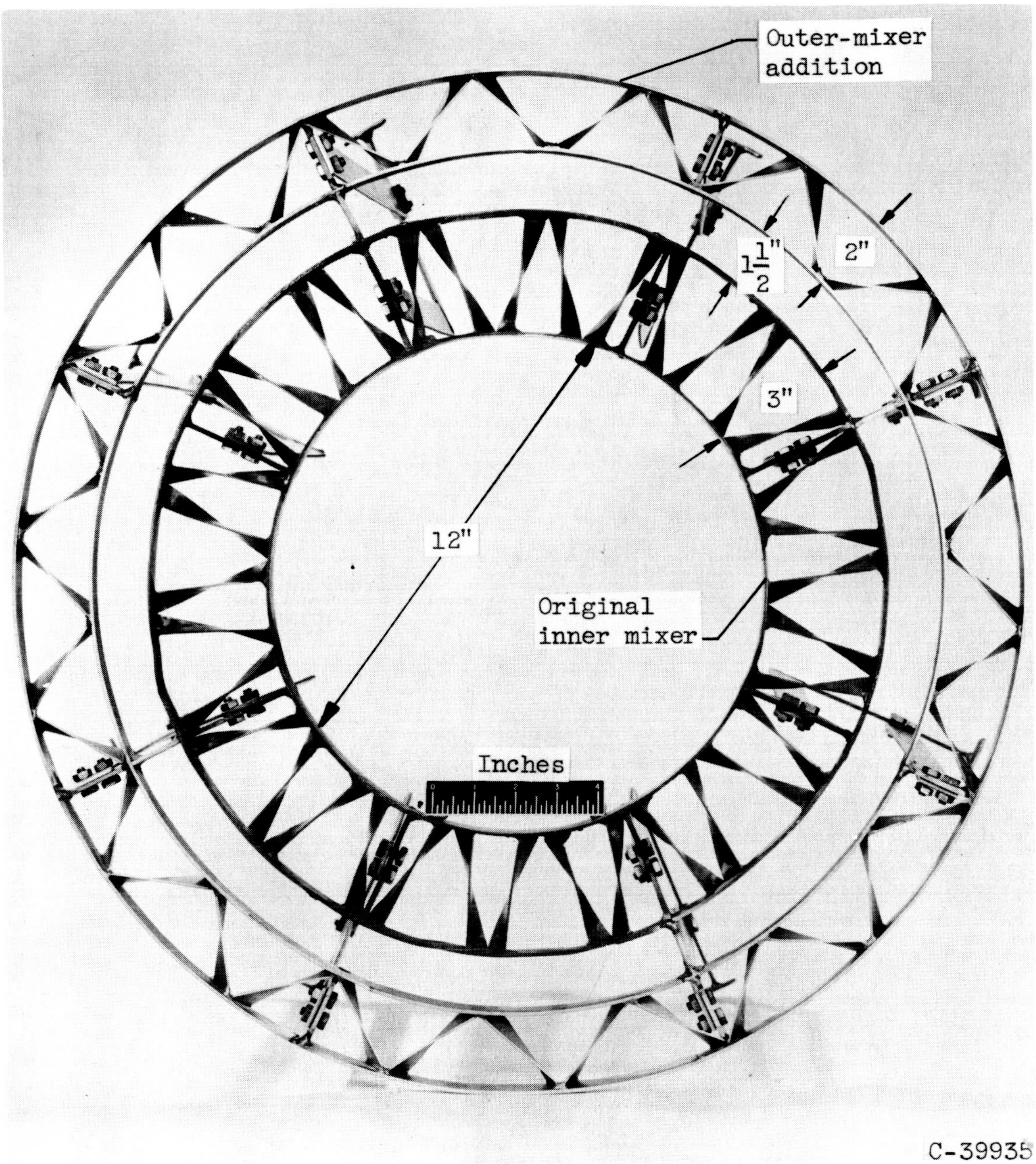
Figure 7. - Reference two-V-gutter flameholder (configuration 1) mounted in afterburner (looking downstream).



(a) Vortex-generator type (configuration 2).

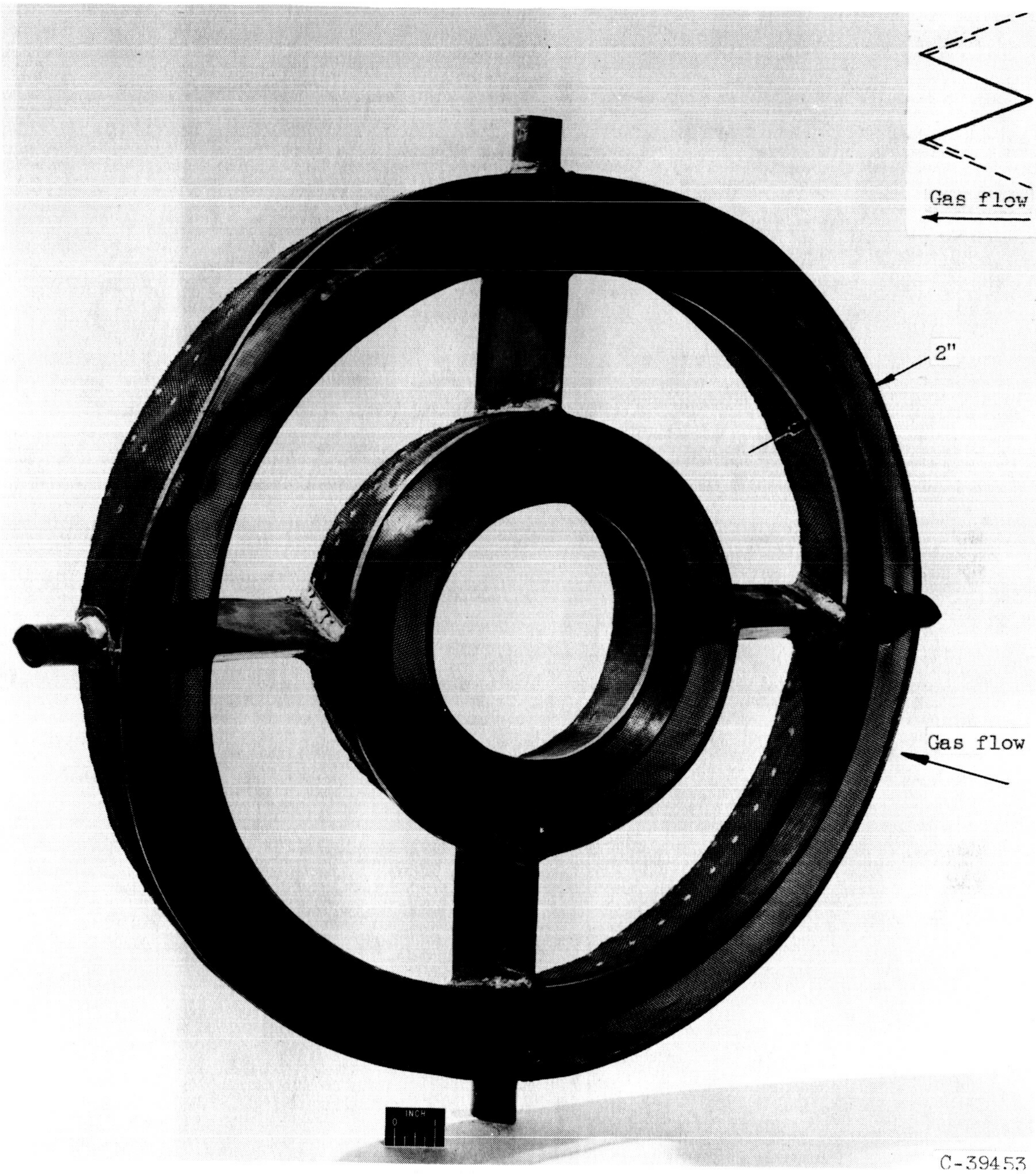
(b) Twisted-vane type (configuration 3).

Figure 8. - Mixer configurations.



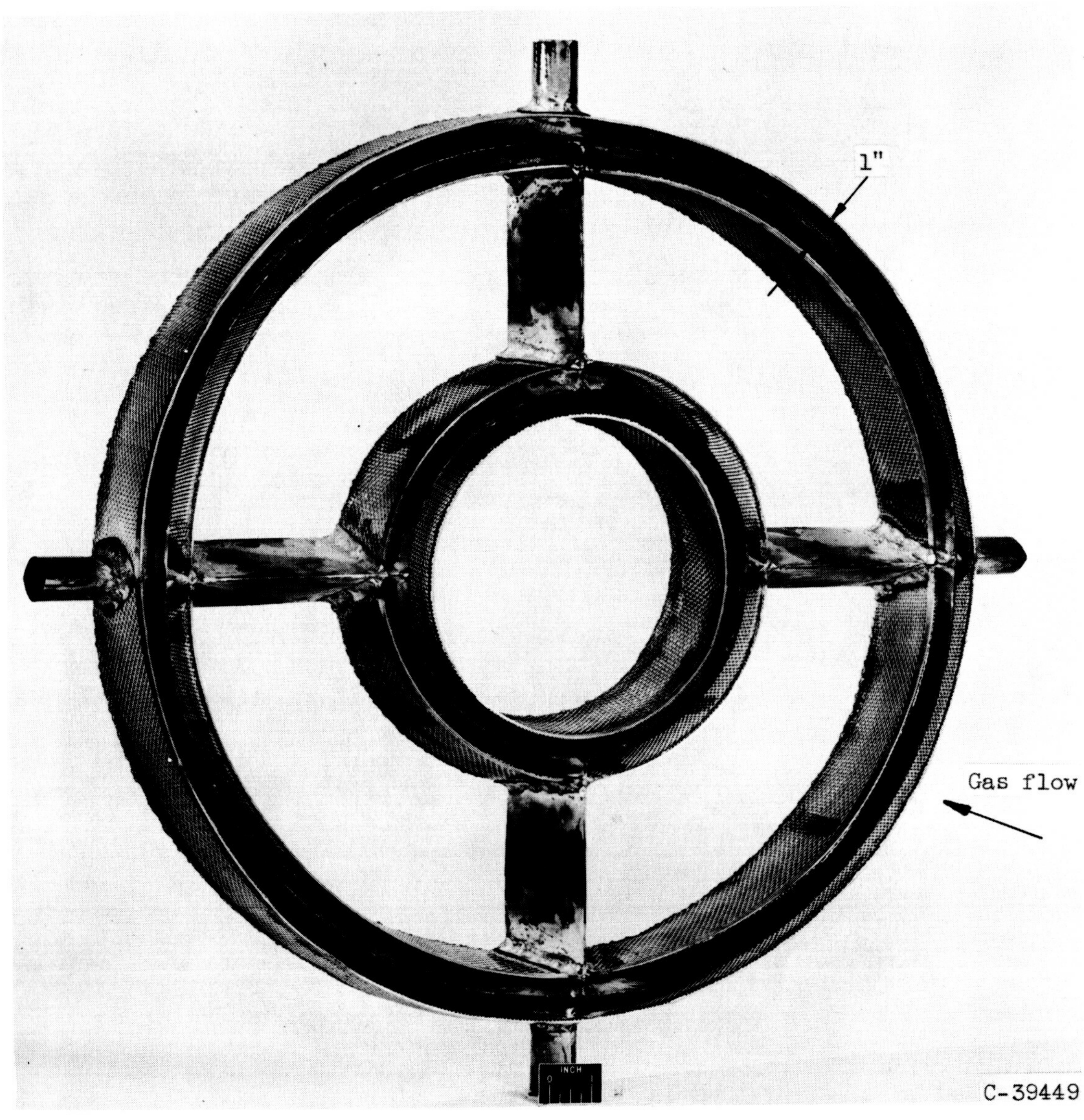
(c) Inner and outer mixer assembly (configuration 4).

Figure 8. - Concluded. Mixer configurations.



(a) 16-Mesh screen plus $1\frac{1}{4}$ inches of 16-mesh overlay (configuration 5).

Figure 9. - Reference two-V-gutter flameholder with screen additions (front view).



(b) 10-Mesh screen (configuration 6).

Figure 9. - Concluded. Reference two-V-gutter flameholder with screen additions (front view).

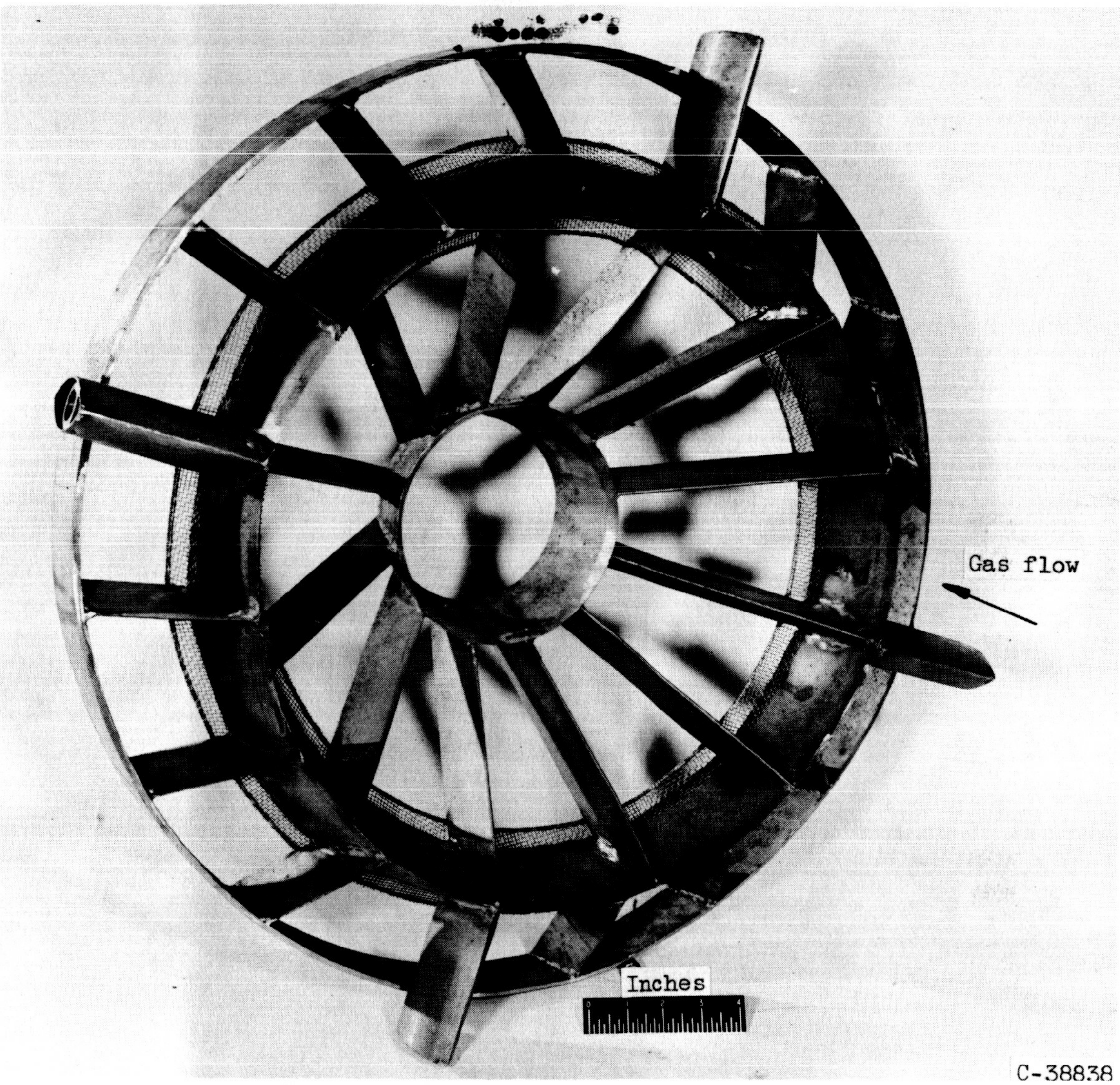
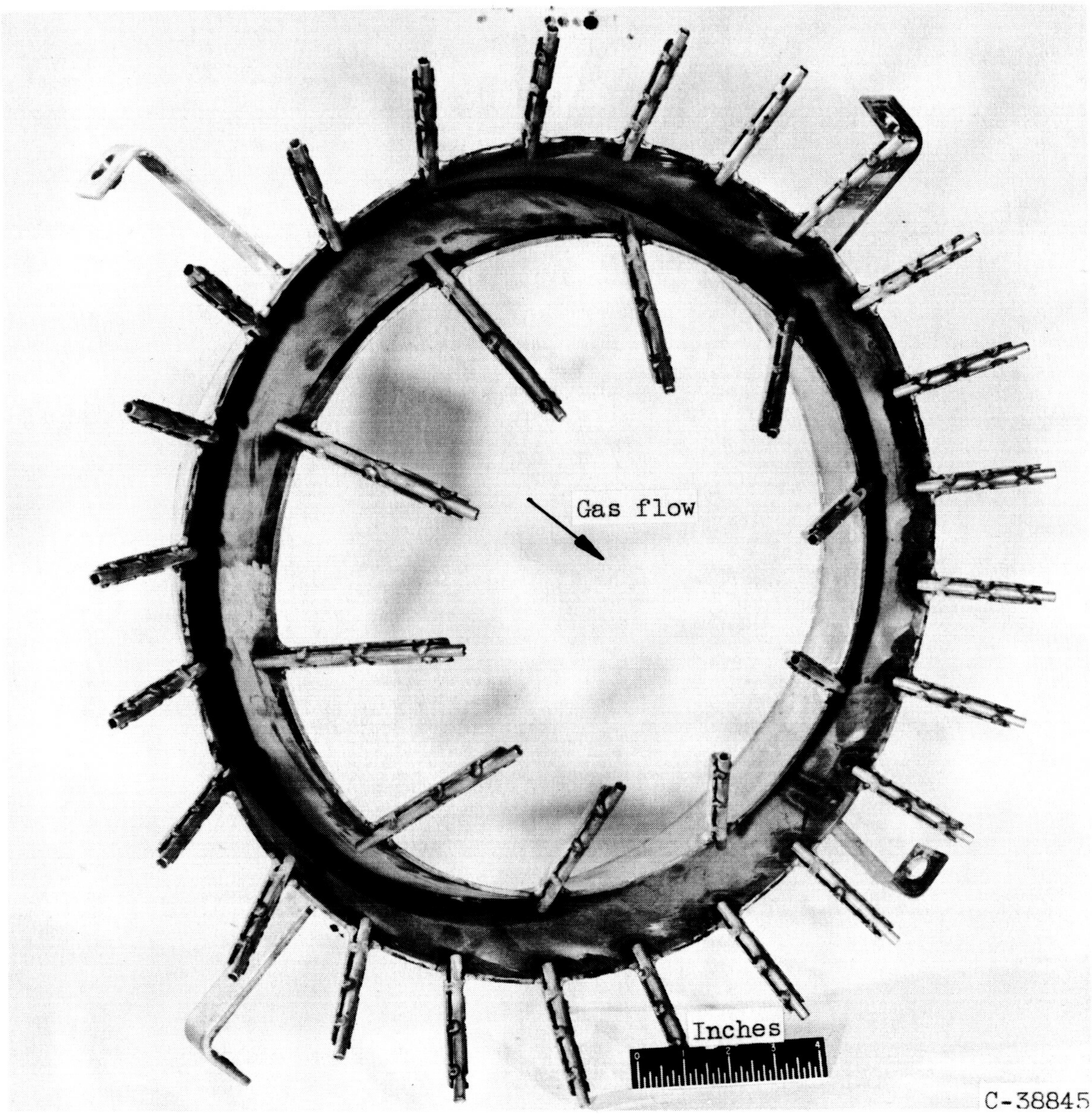
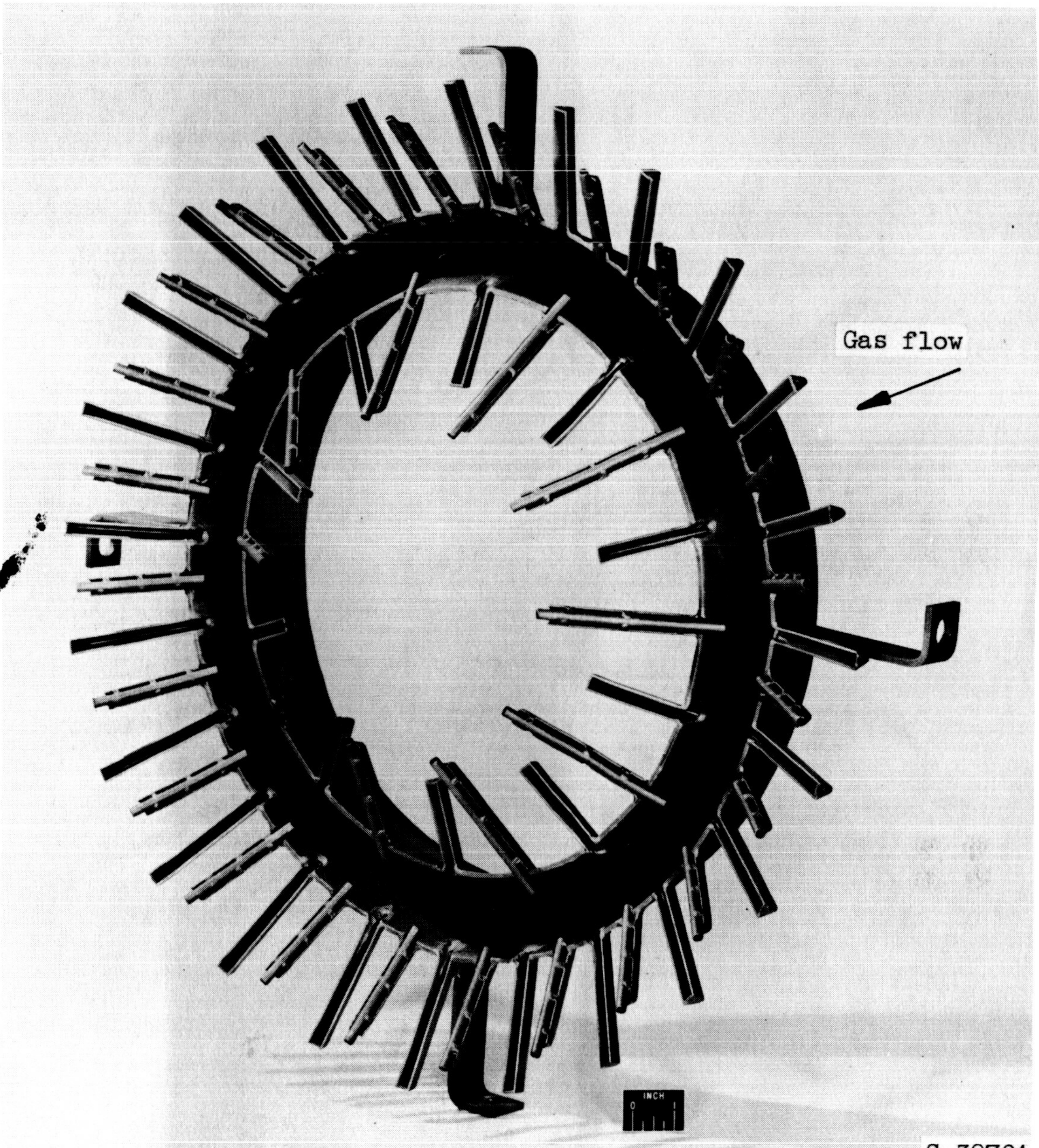


Figure 10. - Single-V-gutter flameholder with 10-mesh screen addition (configuration 7, front view).



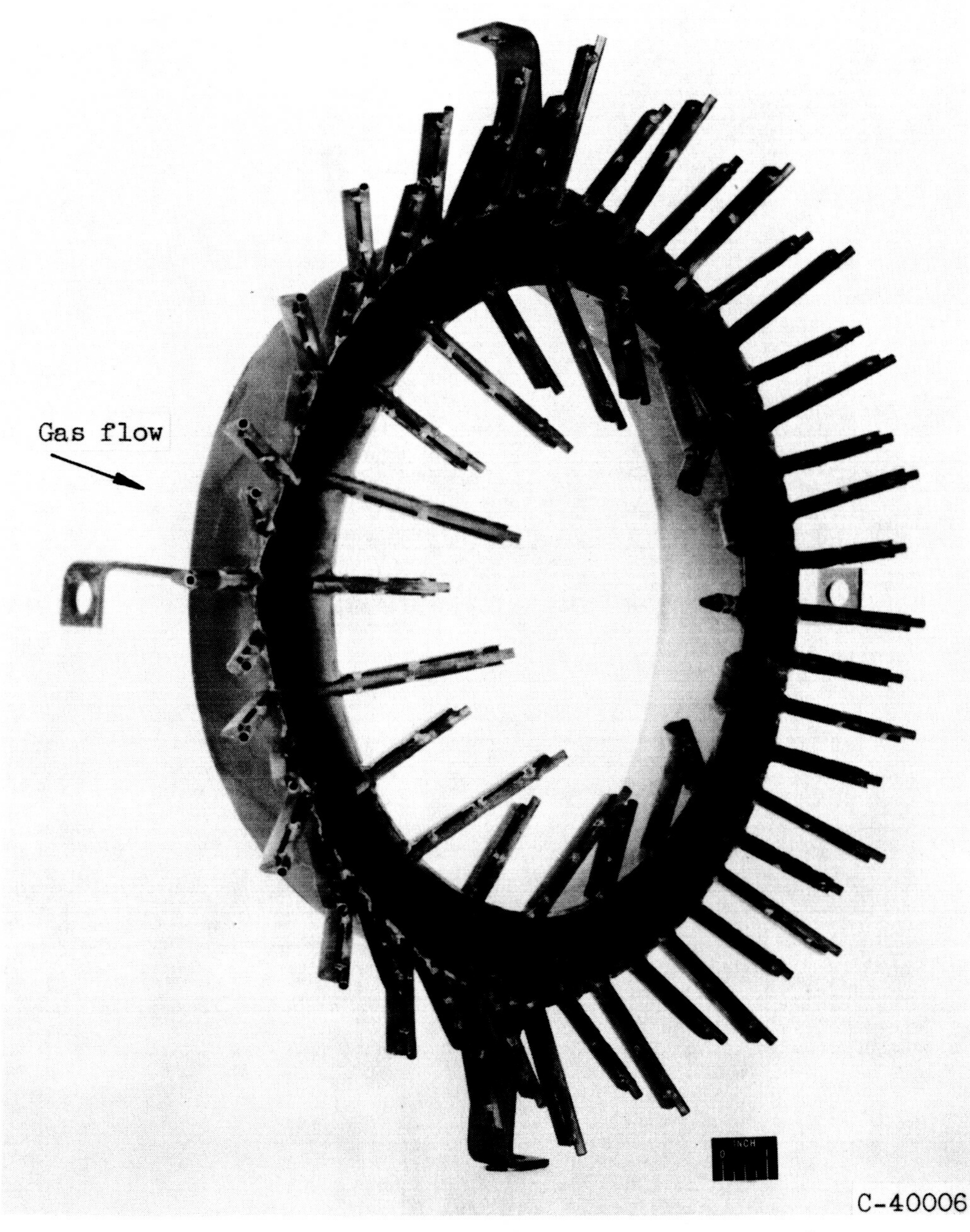
(a) Single V-gutter plus 24 outer tubes and 10 inner tubes (configuration 8).

Figure 11. - Flame-spreader flameholders (rear view).



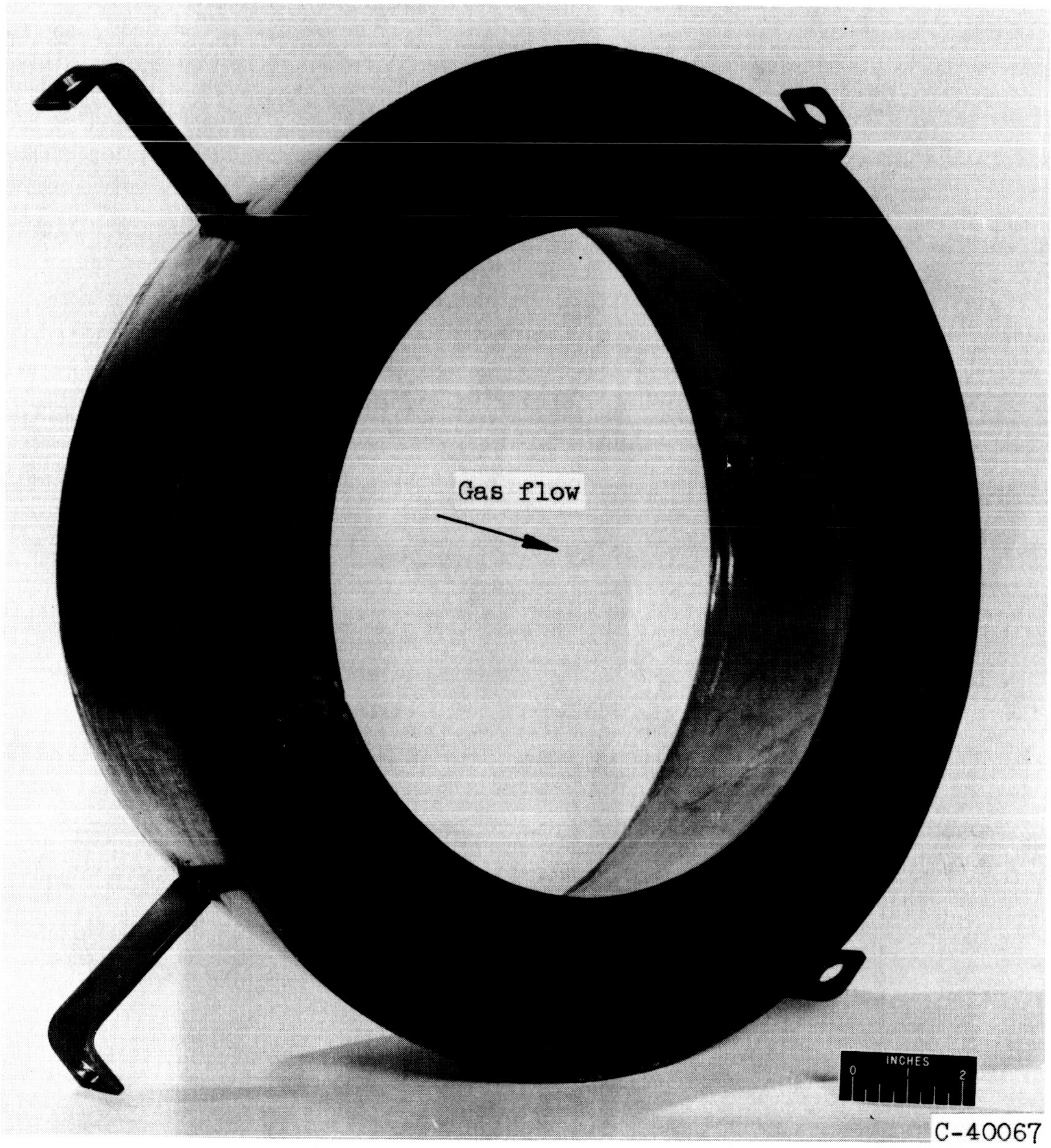
(b) Single V-gutter plus 24 outer tubes, 24 outer gutters, 10 inner tubes, and 10 inner gutters (configuration 9). [redacted]

Figure 11. - Continued. Flame-spreader flameholders (rear view).



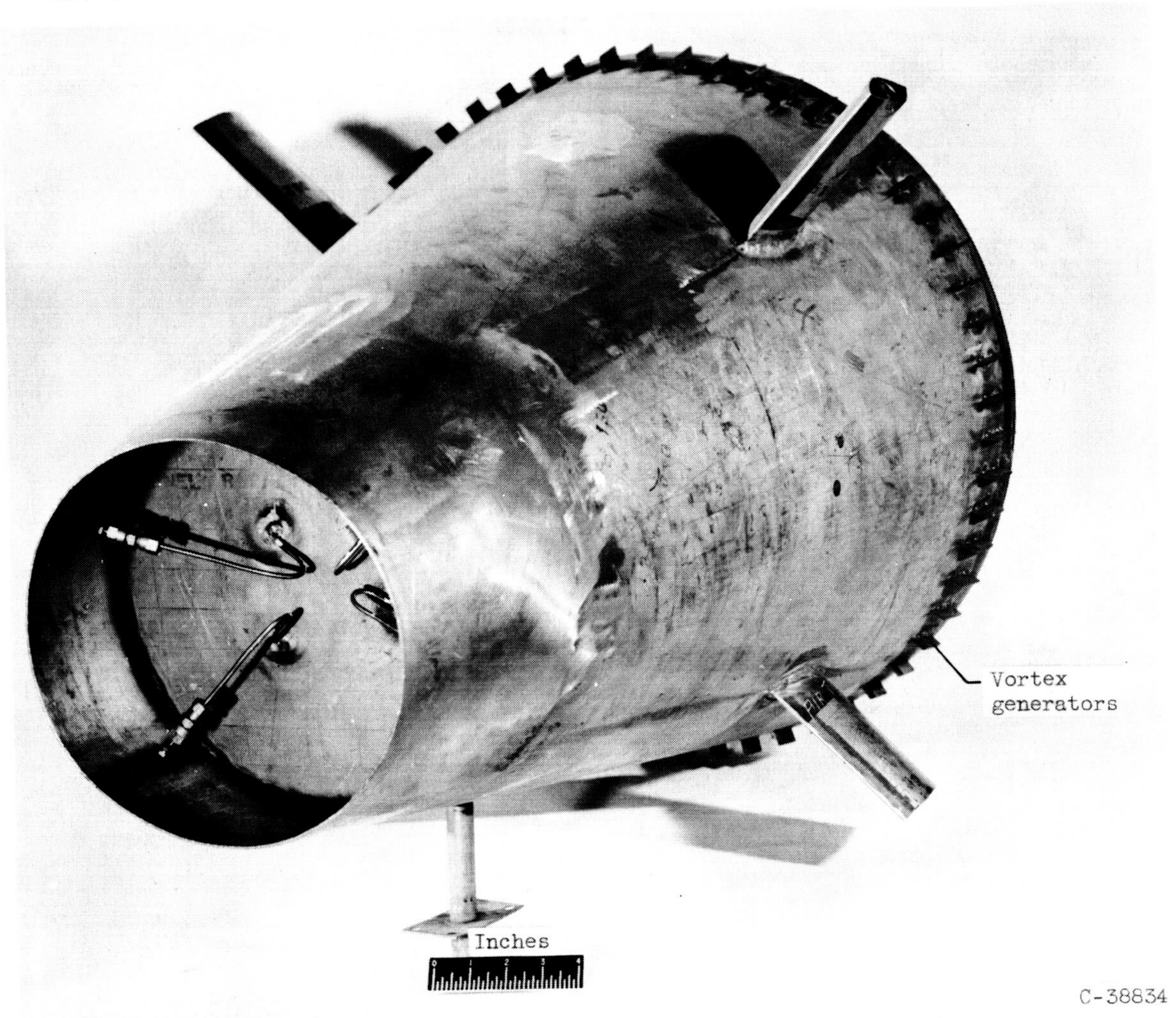
(c) Single V-gutter plus 48 outer tubes and 20 inner tubes (configuration 10).

Figure 11. - Continued. Flame-spreader flameholders (rear view).



) Single V-gutter with same blockage as configuration 10 (fig. 11(c)) but no trailing tubes (configuration 11).

Figure 11. - Concluded. Flame-spreader flameholders (rear view).



Diffuser inner body

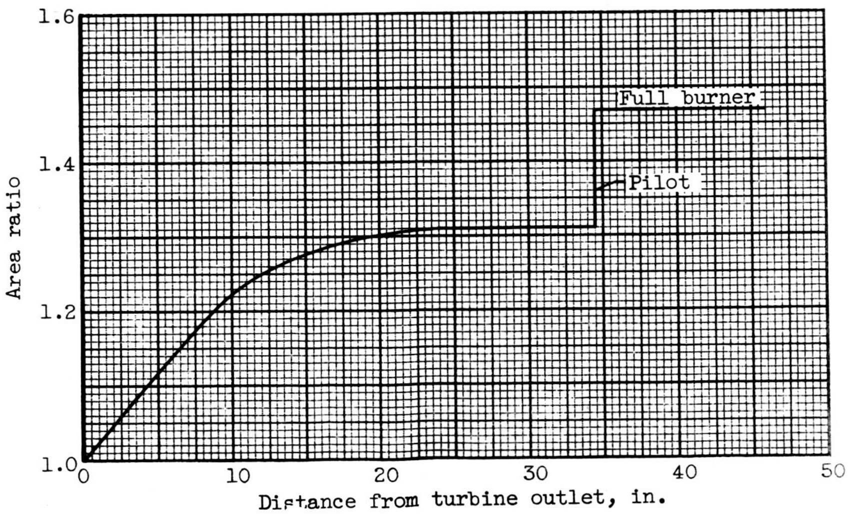
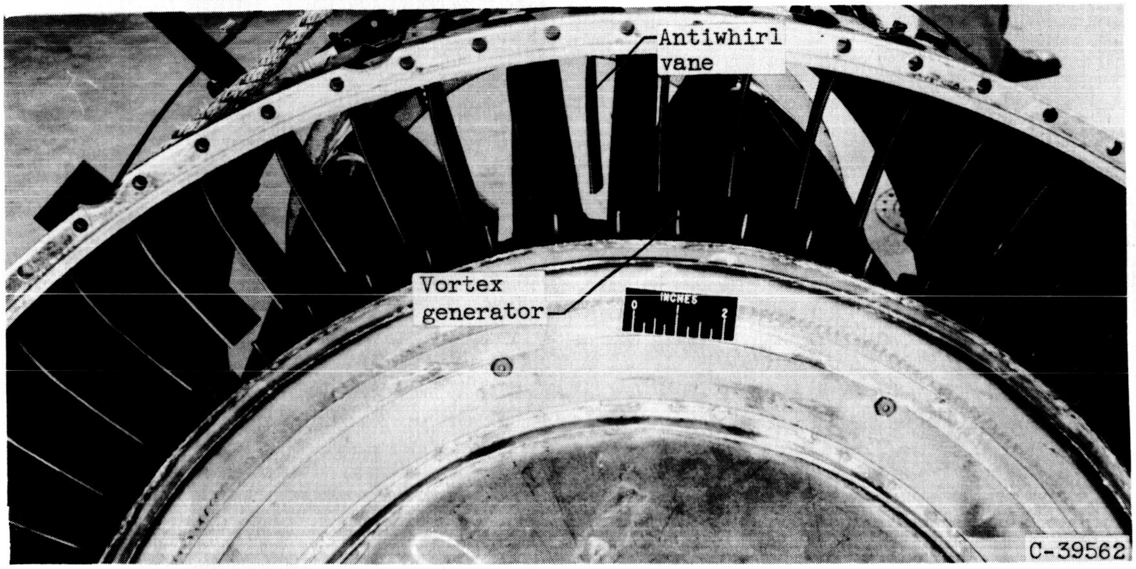


Figure 12. - Variation of diffuser area ratio with distance from turbine discharge.



Antiwhirl vanes and vortex generators mounted at diffuser inlet (looking downstream)

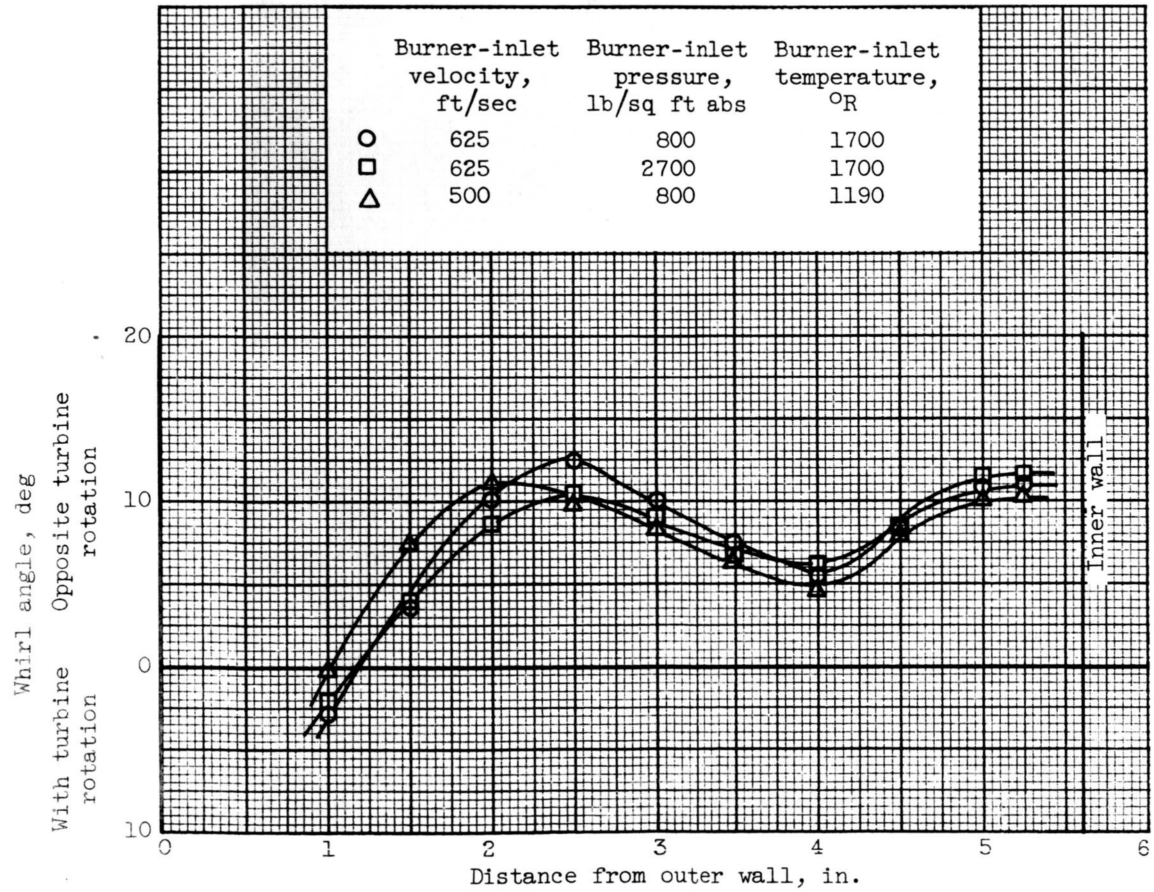


Figure 13. - Effect of burner-inlet velocity and pressure on whirl angle as measured $14\frac{1}{2}$ inches downstream of turbine outlet.

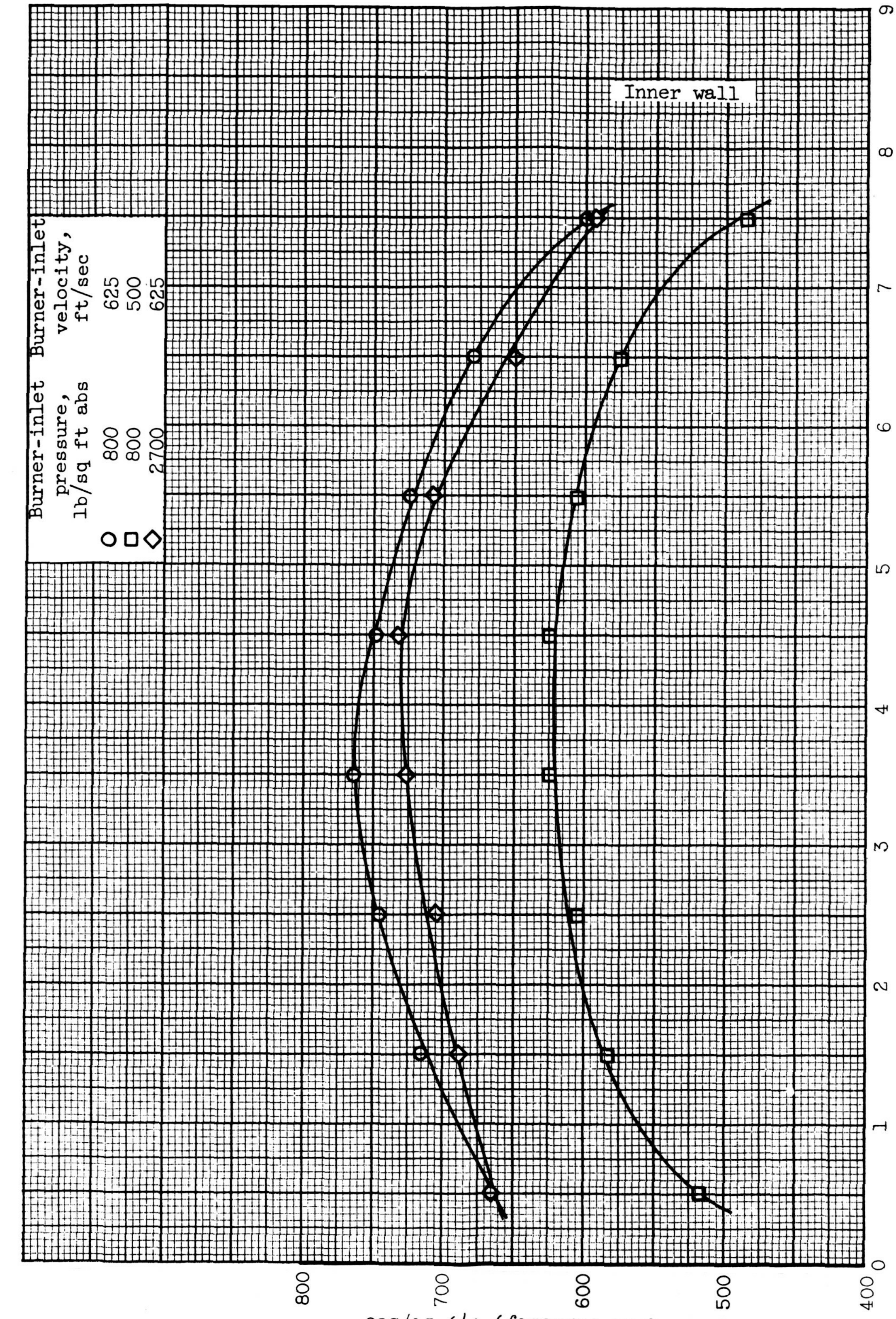


Figure 14. - Effect of burner-inlet pressure and velocity on velocity profile at diffuser outlet, station 7.

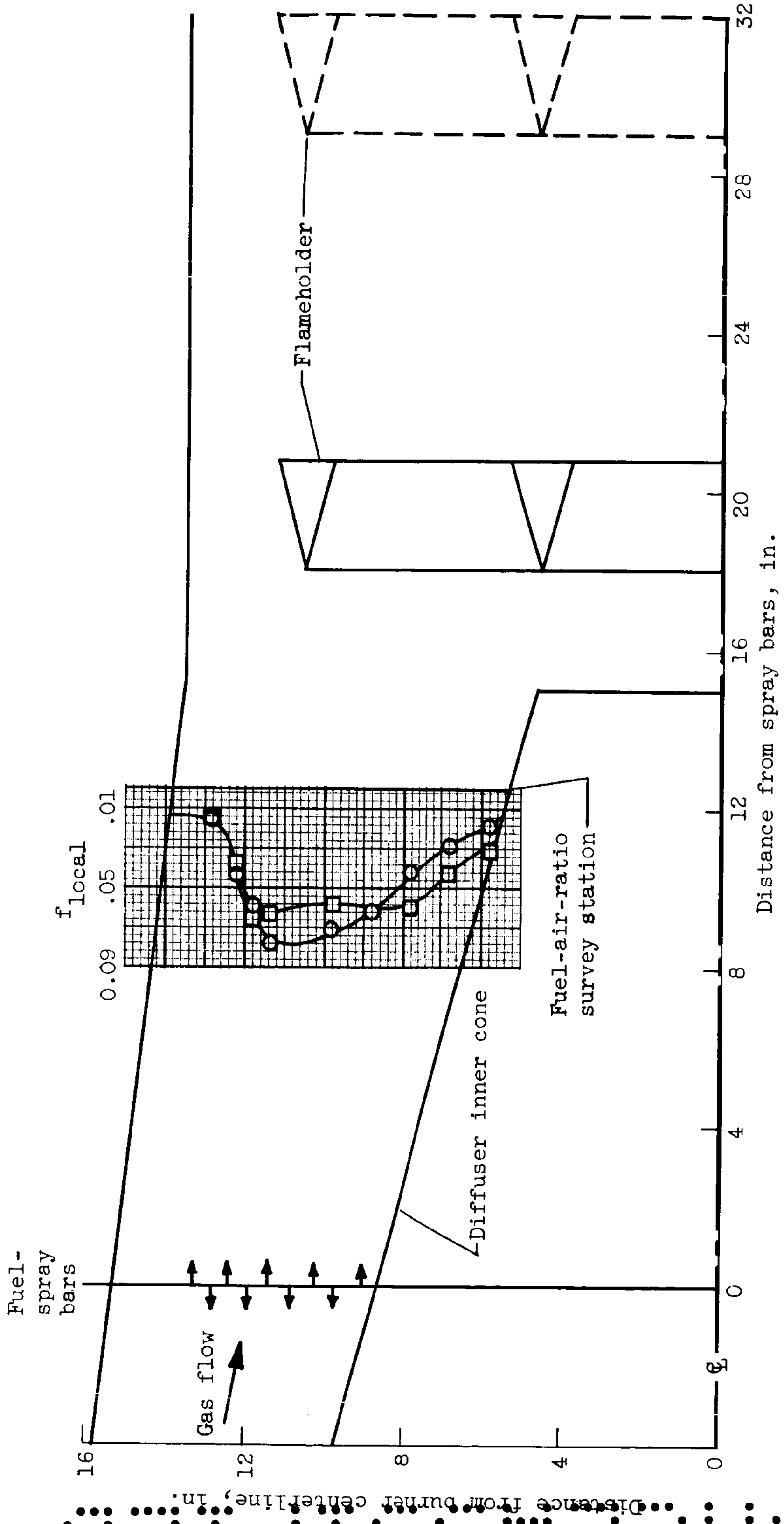


Figure 15. - Effect of burner-inlet pressure on fuel-air ratio. Rated engine operation.

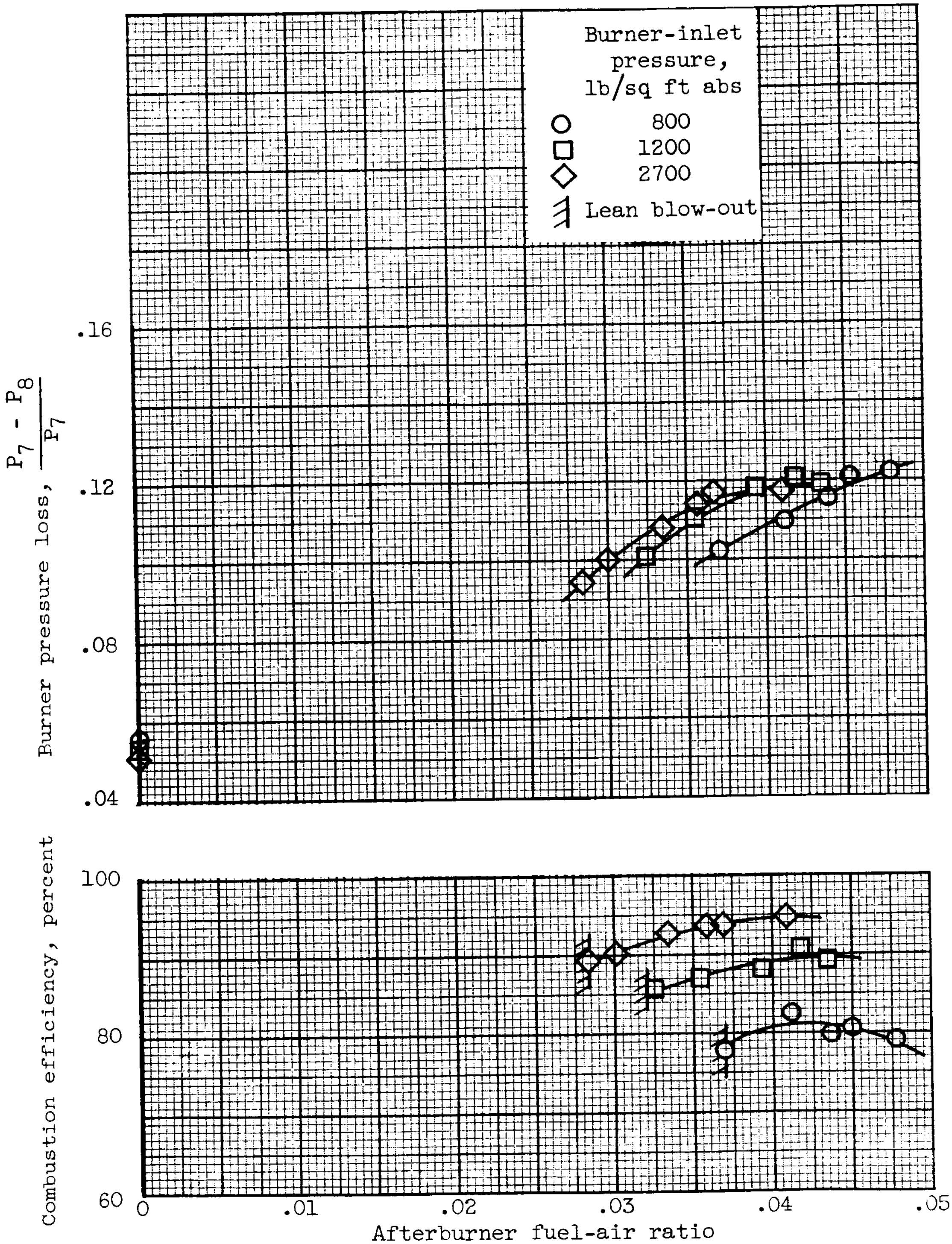


Figure 16. - Variation in performance of reference two-V-gutter flameholder with afterburner fuel-air ratio for three burner-inlet pressures. Burner-inlet velocity, 625 feet per second; burner length, 57 inches.

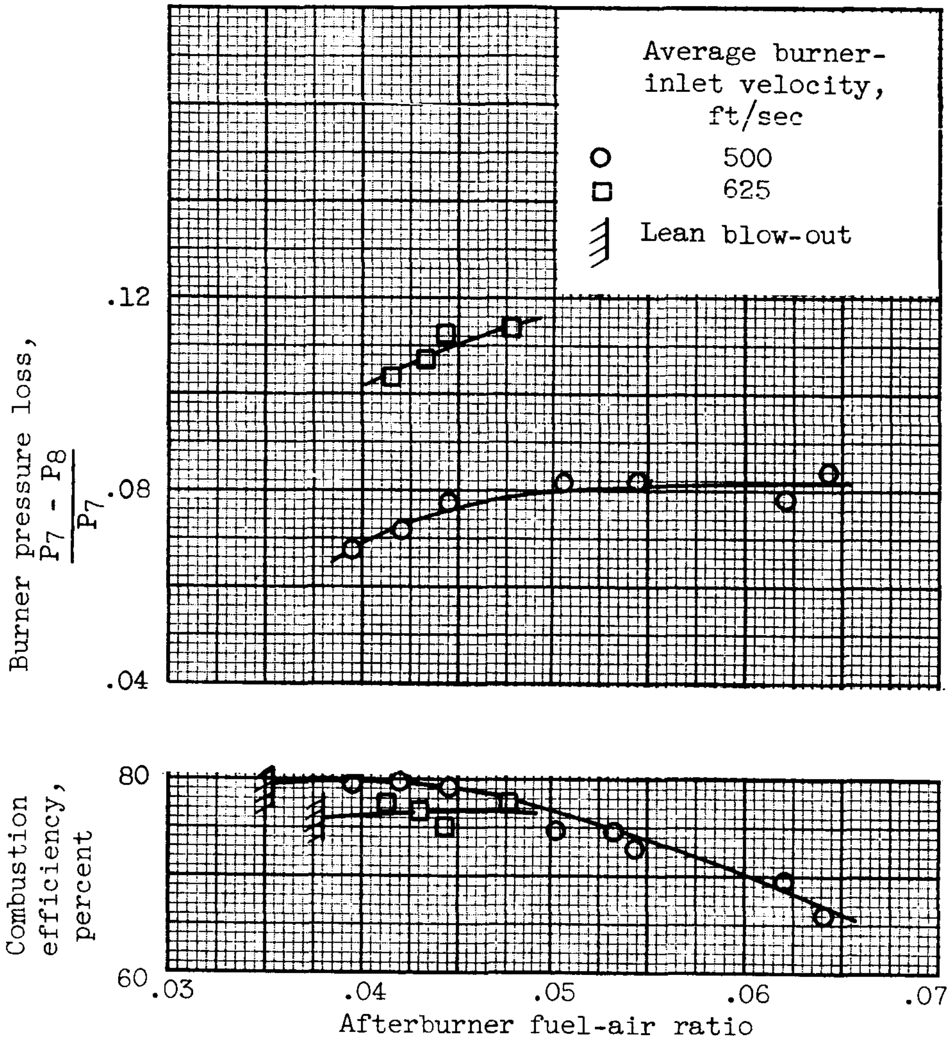
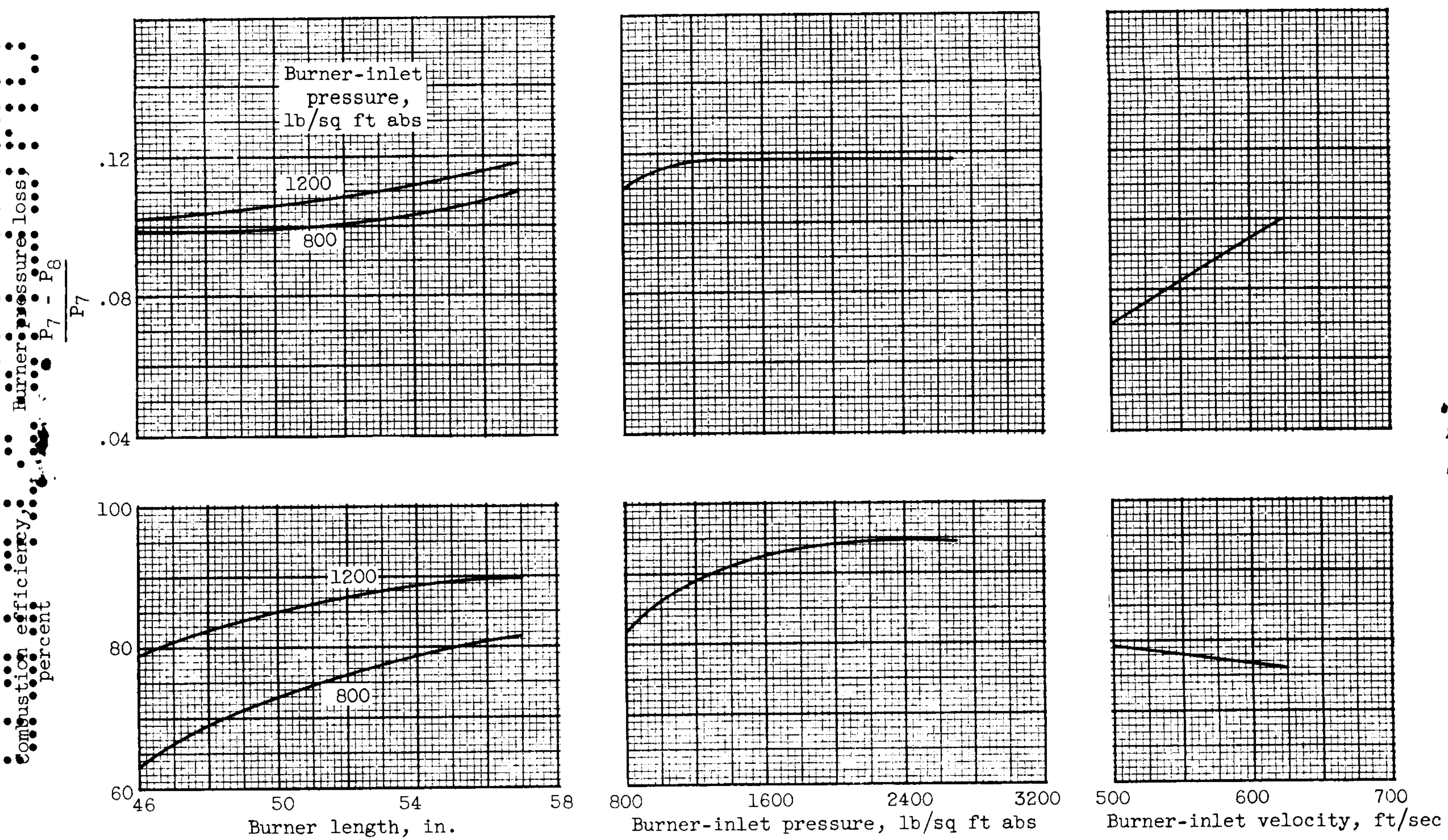


Figure 17. - Effect of burner-inlet velocity on afterburner performance for reference two-V-gutter flameholder. Burner-inlet pressure, 800 pounds per square foot absolute; burner length, 51 inches.

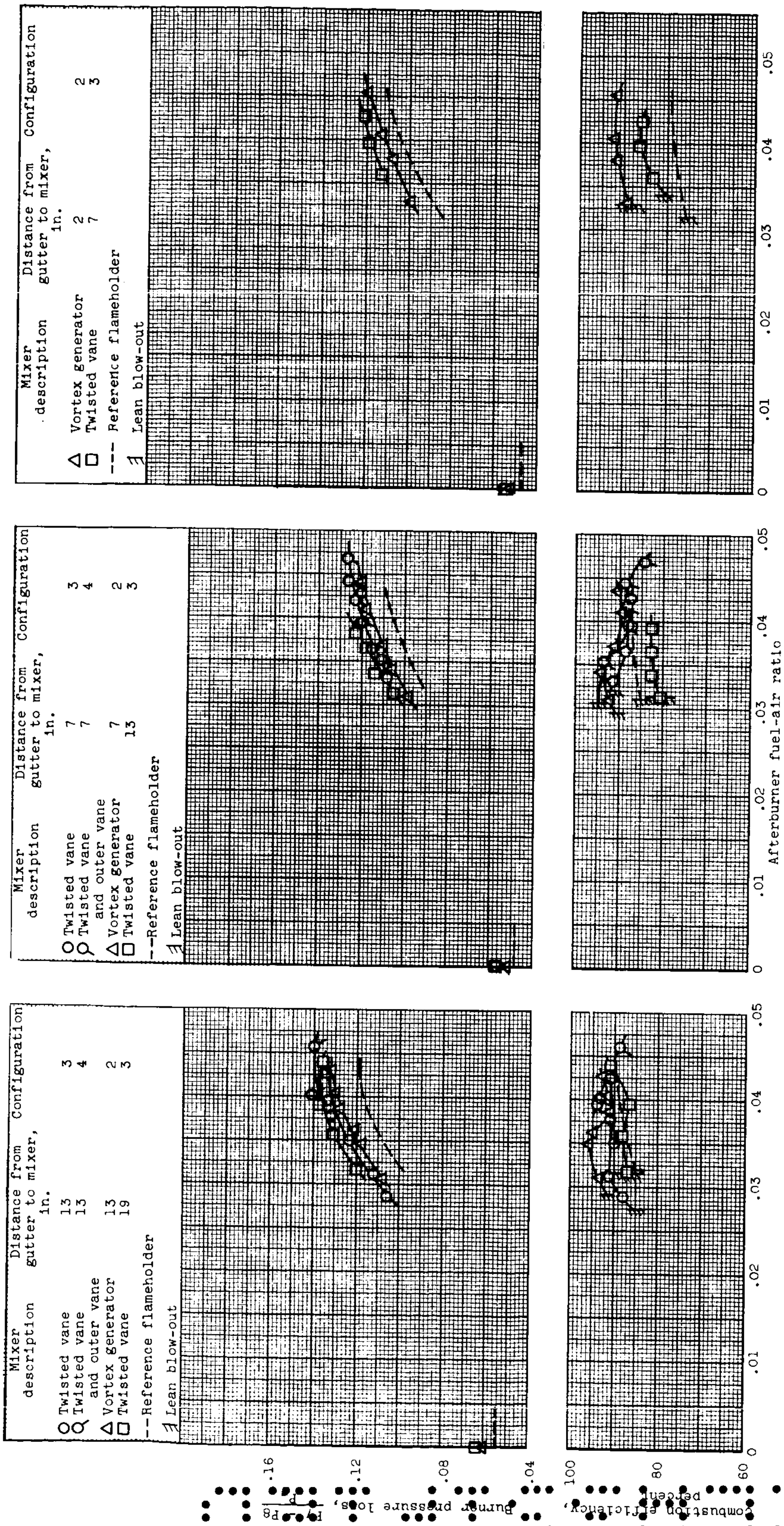


(a) Effect of burner length. Burner-inlet velocity, 625 feet per second.

(b) Effect of burner-inlet pressure, Burner-inlet velocity, 625 feet per second; burner length, 57 inches.

(c) Effect of burner-inlet velocity. Burner-inlet pressure, 800 pounds per square foot absolute; burner length, 51 inches.

Figure 18. - Effect of burner length, burner pressure and burner-inlet velocity on afterburner performance. Reference two-V-gutter flameholder; afterburner fuel-air ratio, 0.040.



(a) Burner length, 57 inches.

(b) Burner length, 51 inches.

(c) Burner length, 46 inches.

Figure 19. - Variation in afterburner performance by installation of several mixer configurations downstream of reference two-V-gutter flameholder. Burner-inlet pressure, 1200 pounds per square foot absolute.

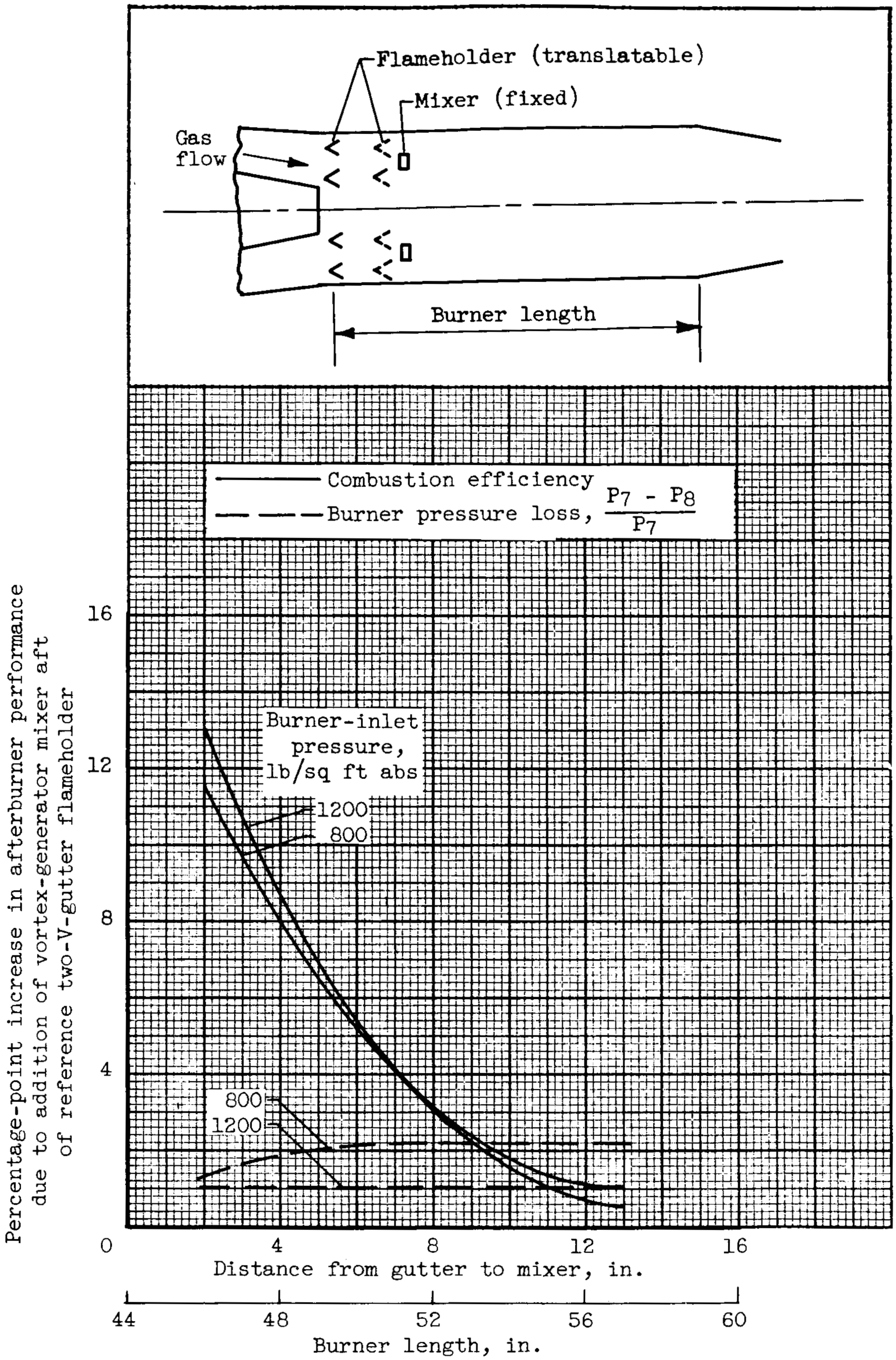


Figure 20. - Effect of gutter-mixer spacing on afterburner performance. Burner-inlet velocity, 625 feet per second; afterburner fuel-air ratio, 0.040. Vortex-generator mixer.

[redacted]

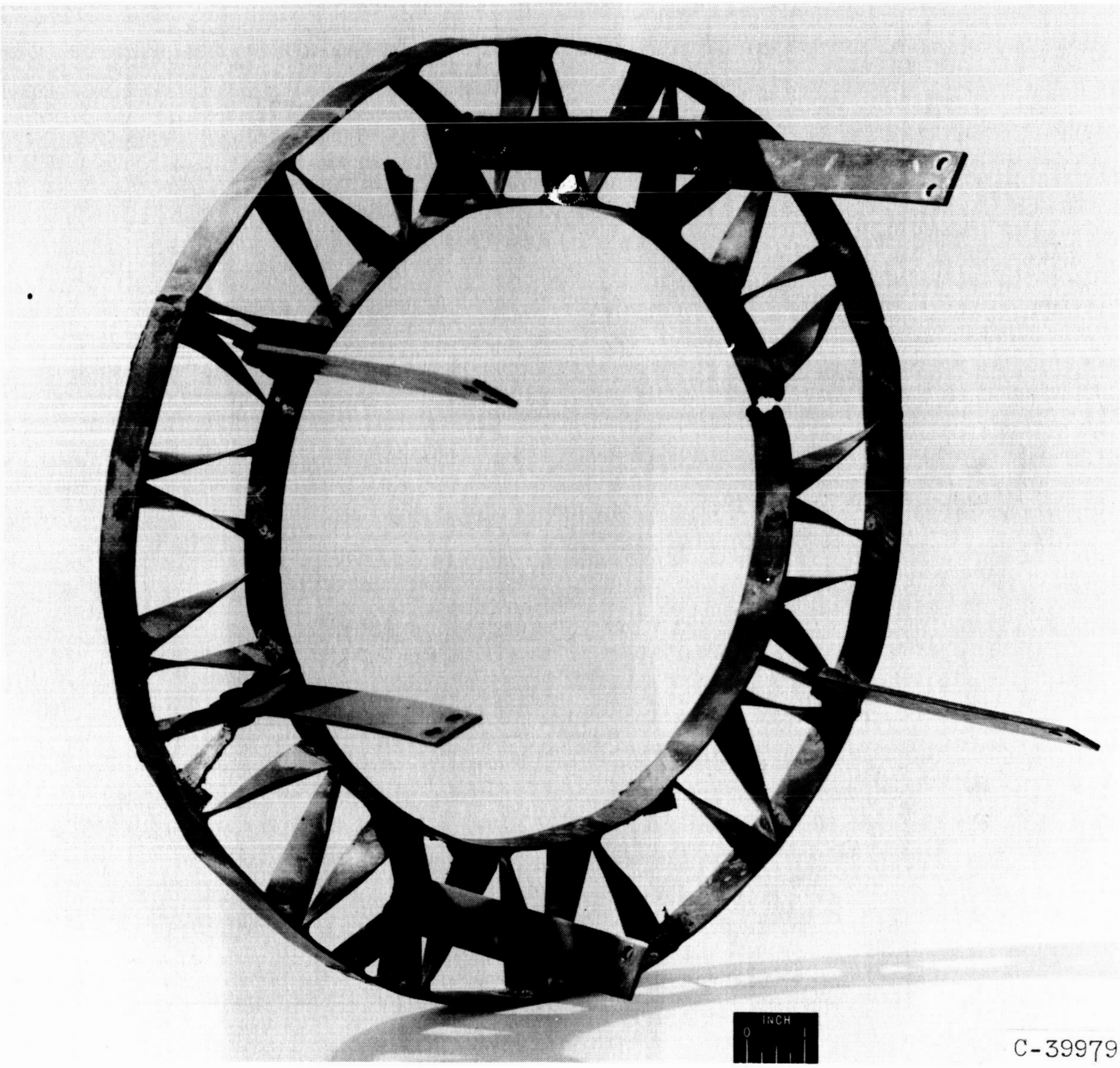
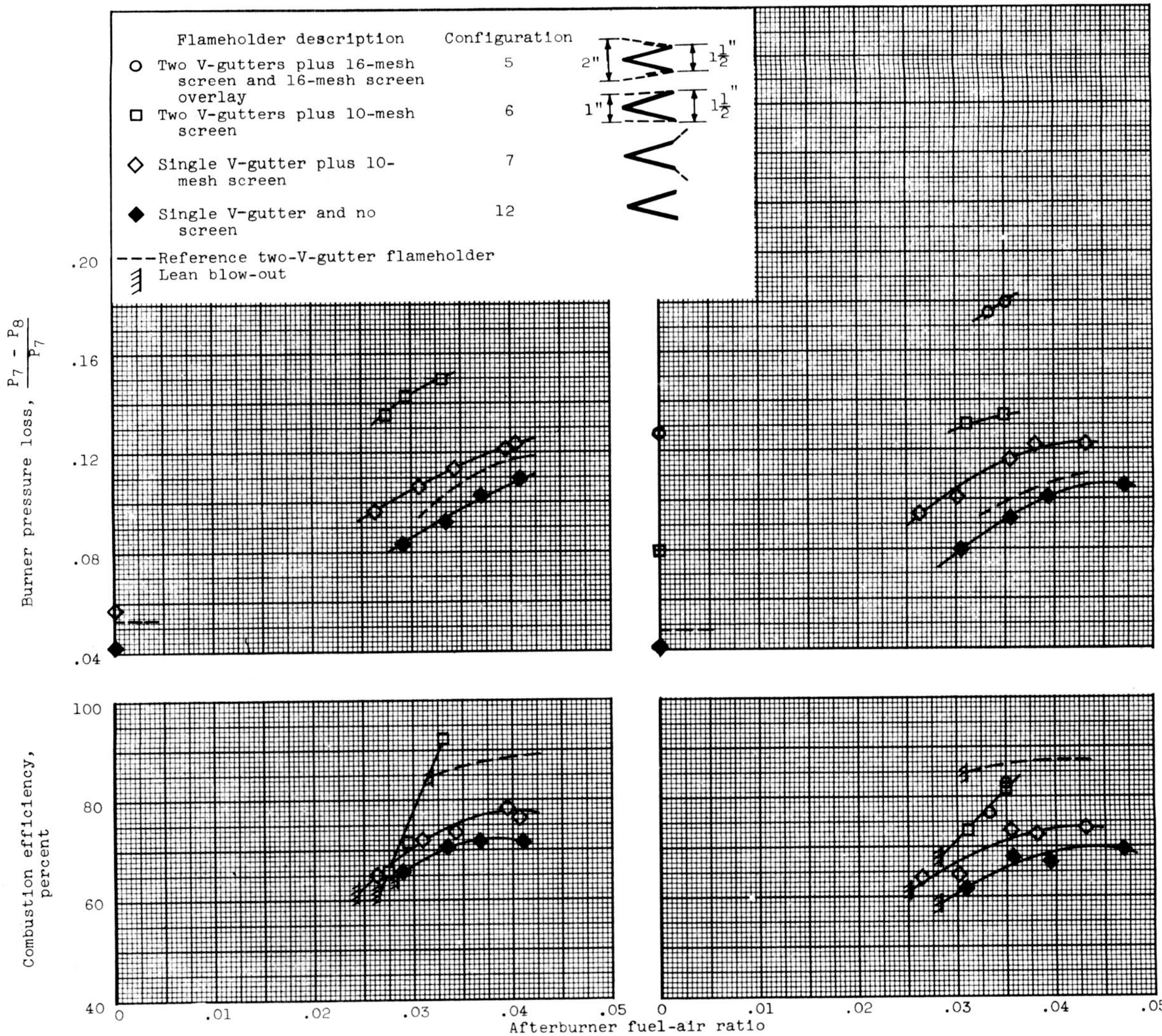


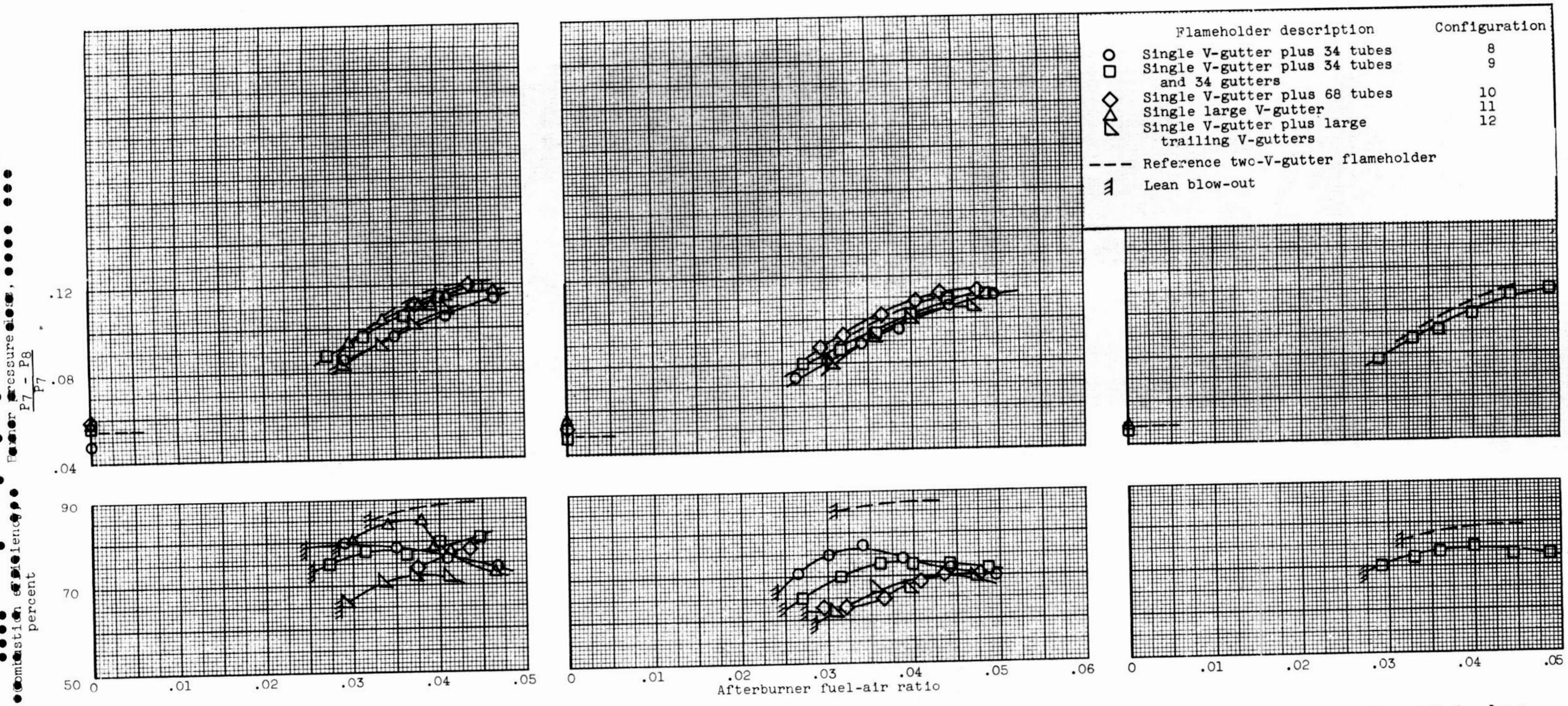
Figure 21. - Photograph of twisted-vane mixer showing damage to elements.



(a) Burner length, 57 inches.

(b) Burner length, 51 inches.

Figure 22. - Effect of application of screen configurations to V-gutter elements on afterburner performance. Burner-inlet pressure, 1200 pounds per square foot absolute.



(a) Burner length, 57 inches.

(b) Burner length, 51 inches.

(c) Burner length, 46 inches.

Figure 23. - Variation of afterburner performance with fuel-air ratio for several flame-spreader flameholders. Burner-inlet pressure, 1200 pounds per square foot absolute.

Trailing element	Description
1	1/2" Gutter plus 1/4" tube (final configuration)
2	1/2" Gutter plus 3/16" tube
3	1/2" Gutter plus solid 1/4" rod
4	1/2" Gutter

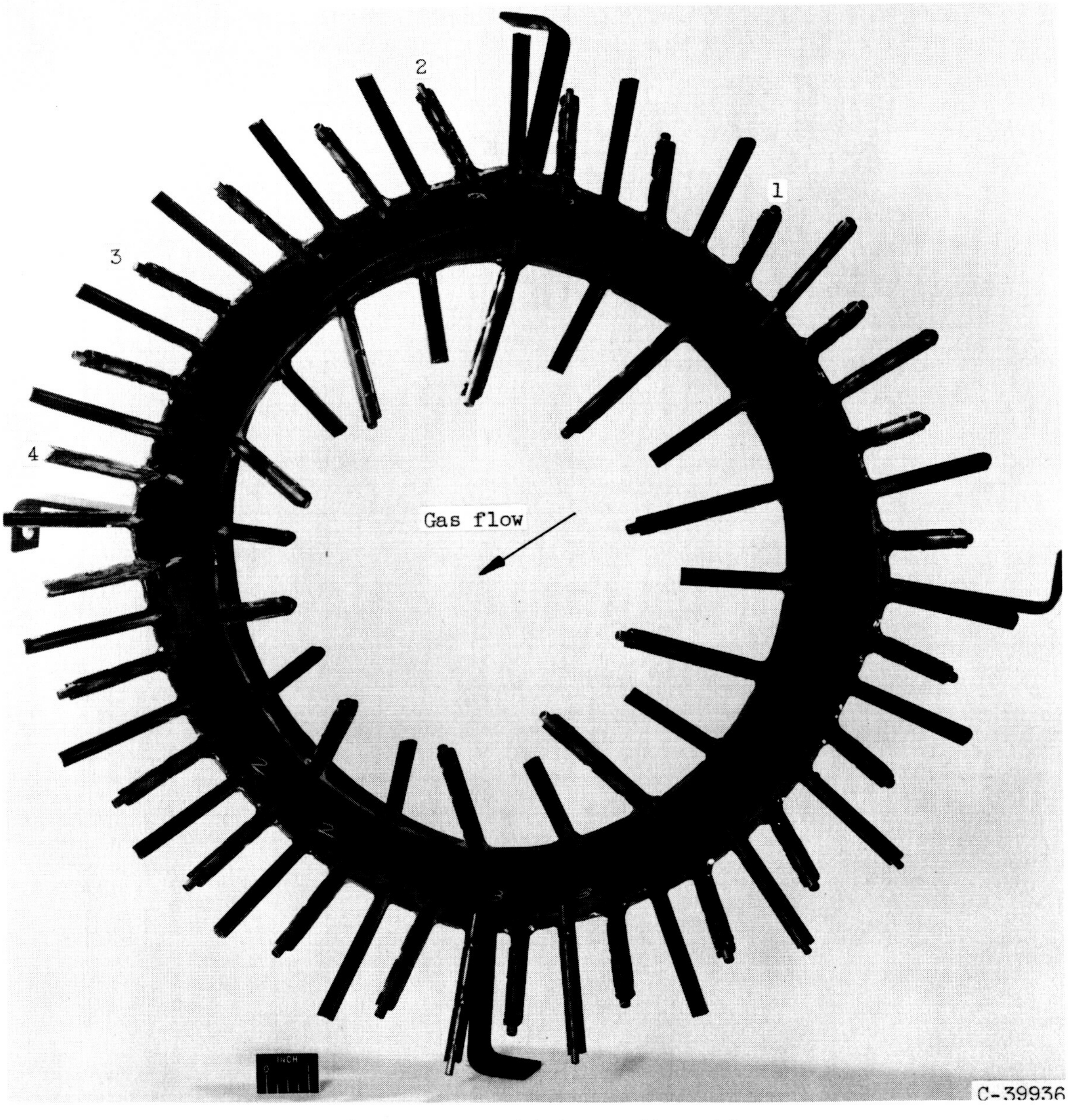


Figure 24. - Assorted tube configurations.

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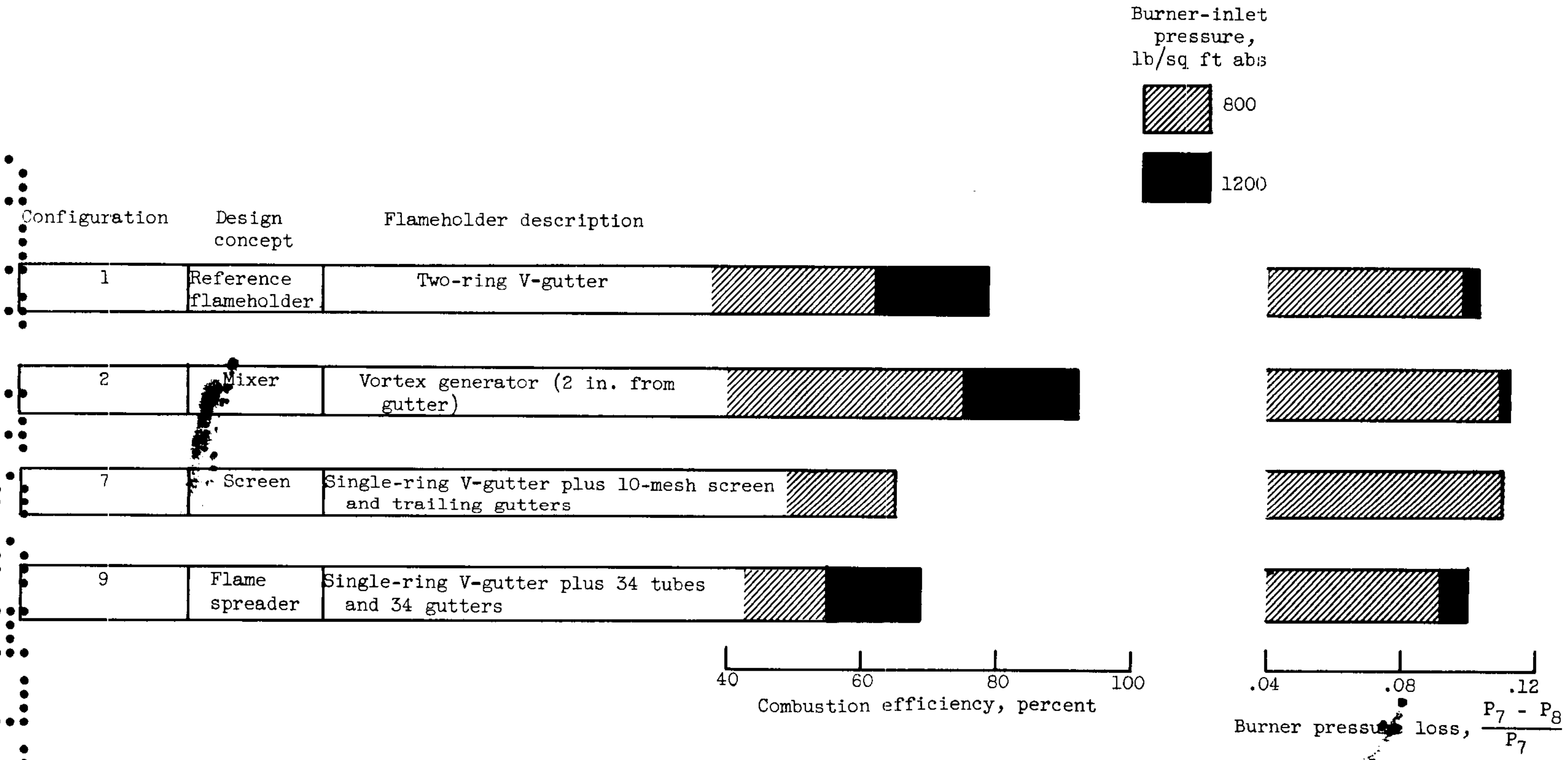

Figure 25. - Performance summary of optimum flameholder configuration from each design concept. Burner-inlet velocity, 625 feet per second; afterburner fuel-air ratio, 0.040; burner length, 46 inches.

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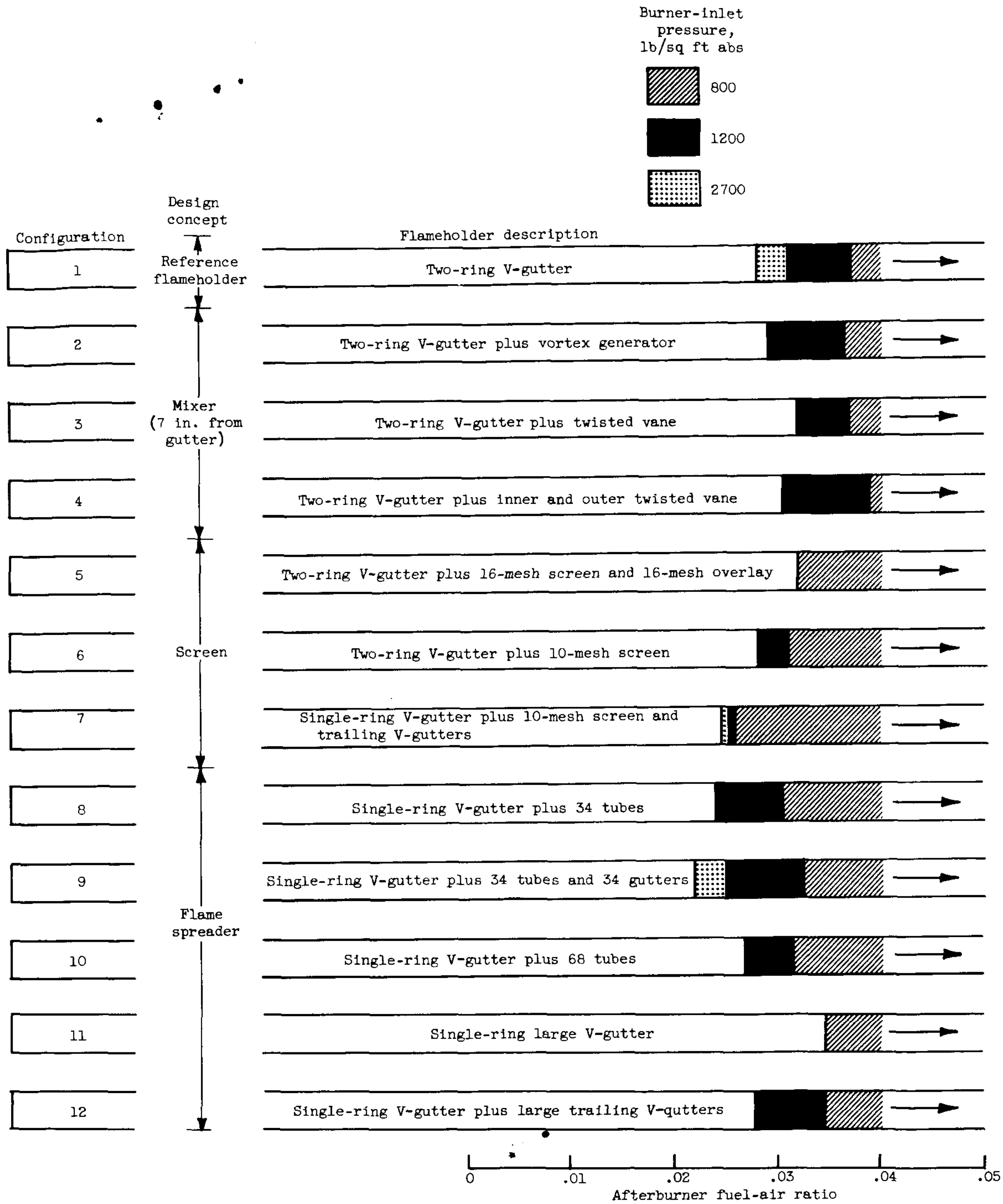
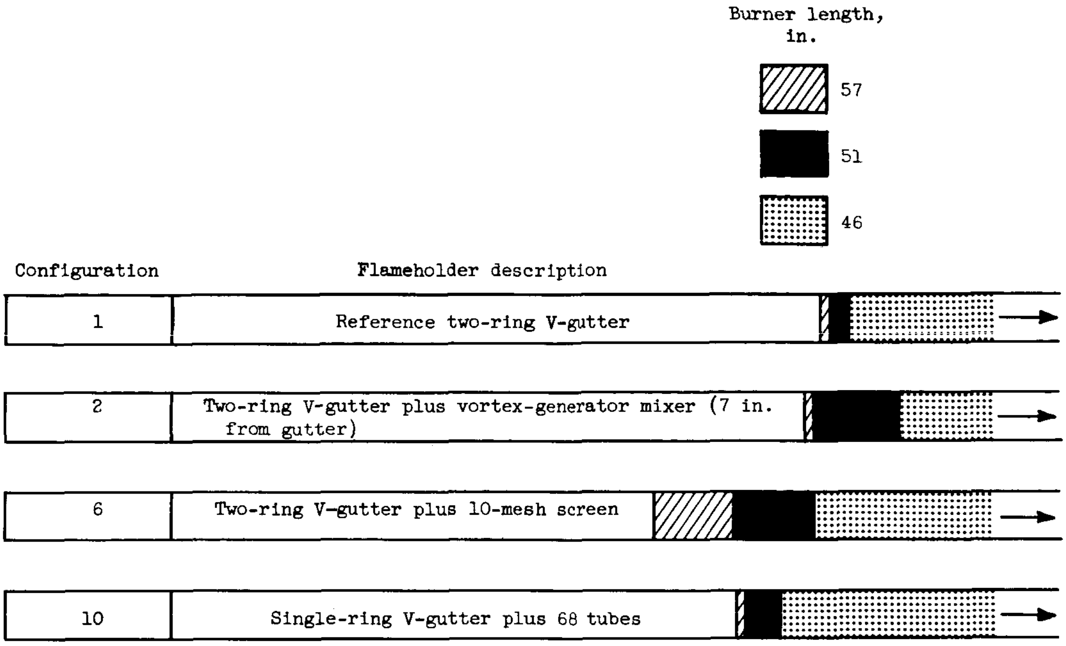
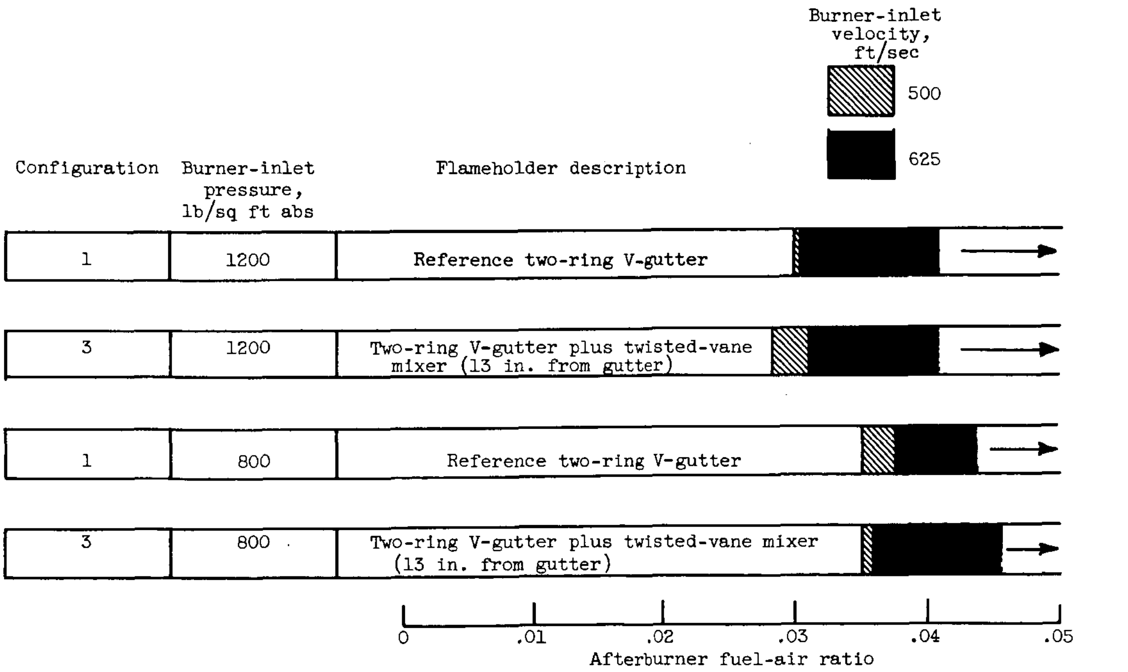


Figure 26. - Evaluation of the lean stability limits of various configurations over range of burner-inlet pressures. Burner-inlet velocity, 625 feet per second; burner length, 51 inches.



(a) Effect of burner length. Burner-inlet pressure, 800 pounds per square foot absolute.



(b) Effect of burner-inlet velocity.

Figure 27. - Effect of burner length and burner-inlet velocity on lean blow-out characteristics of several flameholder configurations.