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RESEARCH MEMORANDUM

PHOTOGRAPHIC INVESTIGATION OF AIR-FLOW PATTERNS IN TRANSPARENT ONE-SIXTH SECTOR OF ANNULAR TURBOJET-ENGINE COMBUSTOR WITH AXIAL-SLOT-TYPE AIR ADMISSION

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RESEARCH MEMORANDUM

PHOTOGRAPHIC INVESTIGATION OF AIR-FLOW PATTERNS IN TRANSPARENT ONE-SIXTH SECTOR OF ANNULAR TURBOJET-ENGINE COMBUSTOR WITH AXIAL-SLOT-TYPE AIR ADMISSION

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SUMMARY

A study was made of gross air-flow patterns in a transparent one-sixth sector of an NACA experimental annular turbojet-engine combustor with axial slots for air admission. Flow patterns under cold-flow conditions were determined in longitudinal and cross-sectional planes by the use of high-speed flash photographs of balsa-dust flow tracers. Photographs were taken at combustor reference velocities from 26 to 72 feet per second.

Photographs of the combustor primary zone along the longitudinal plane disclosed a low-velocity recirculation region near the fuel manifold. The velocity and the quantity of air involved in the recirculation region appeared to be appreciably less than those found in a tubular combustor during a previous investigation. Photographs of the combustor secondary zone along the cross-sectional plane indicated large-scale circulatory air currents which appeared to be markedly affected by the combustor side walls. There appeared to be no significant effect of combustor air velocity on gross flow patterns.

INTRODUCTION

Research at the NACA Lewis laboratory on annular turbojet-engine combustors (refs. 1 and 2) has resulted in the development of several designs giving improved performance. One type of combustor design evolved in this research had axial slots for air admission in both the primary and secondary zones (ref. 2). Combustors having this method of air admission gave improved combustion efficiency over production-model combustors, and also permitted satisfactory control of the outlet-temperature profile. Because of the high performance obtained with slot-type air admission, the gross air-flow patterns accompanying this type of combustor design were investigated. Comparison of such patterns with those obtained with other types of combustor design may indicate the liner configurations best suited to achieve internal flow patterns required for optimum combustor performance.

In a previous investigation (ref. 3), it was found that the gross air-flow patterns in a tubular turbojet-engine combustor could be determined satisfactorily by the use of a transparent model of the combustor and high-speed flash photographs of balsa-dust flow tracers. Accordingly, a similar study was made of the flow patterns in a transparent one-sixth sector of a slot-type annular combustor. Most of the photographs were taken at a reference velocity of 26 feet per second because of equipment limitations. Additional, limited sets of photographs were taken at reference velocities of 53 and 72 feet per second, representative of sea-level starting and altitude cruising conditions, respectively. The tests at the higher velocities were made in order to determine whether flow patterns at normal operating conditions could be predicted from those obtained at low velocities. If such predictions could be made, both design problems and procedures for possible future flow-pattern tests would be simplified. All tests were conducted under cold-flow conditions.

APPARATUS

Combustor. - The photographic study of air-flow patterns was conducted with the transparent, plastic, one-sixth-sector combustor shown in figure 1. The combustor was constructed to simulate combustor model 5 of reference 2. The wall thicknesses of the liner and the outer housing were 1/16 and 1/4 inch, respectively. The location and the geometry of wall-cooling louvres and air-entry slots in the liner are shown in figure 1 and are described more fully in reference 2.

As the result of the high static-pressure drop across the liner wall at higher velocity conditions, the liner had to be strengthened against breakage by bolting it to the outer shell at critical points. The presence of the bolts (1/8-in. diam.) did not appreciably alter the air-flow patterns, as indicated by comparison of photographs taken at the 26-feet-per-second velocity condition before and after the bolts were installed.

A schematic diagram of the combustor installation is presented in figure 2. The test combustor was connected to the laboratory air-supply and exhaust facilities by direct-connect ducting; the air-flow rate and the combustor inlet pressure were regulated by remote-control valves located upstream and downstream of the combustor. Combustor inlet-air temperature was controlled by valves proportioning the amount of air passing through the heat exchanger.

Instrumentation. - Air flow to the combustor was metered by a square-edged orifice, installed according to A.S.M.E. specifications, and located upstream of all regulating valves. Combustor inlet-air temperature was measured by a single-junction iron-constantan thermocouple located at plane 1-1 (fig. 2) and was indicated on a self-balancing potentiometer. The inlet-air pressure was measured by two, six-point total-pressure rakes located at plane 2-2 (fig. 2).

Flow-pattern photographs. - The camera and the light-source positions used in obtaining the reported photographic data are shown in figure 3. Details of the balsa-dust injection system and photographic techniques used in the present investigation are given in the appendix.

PROCEDURE

Air-flow patterns in the transparent one-sixth-sector combustor were obtained by photographing the traces of balsa-dust particles injected into the inlet air stream. The camera was focused and the balsa-dust injection tubes were arranged as described in the appendix. Most of the photographs were taken at a combustor reference velocity (based on maximum cross-sectional area of the combustor flow passage, inlet-air density, and mass air-flow rate) of 26 feet per second. Additional, limited sets of photographs were taken at reference velocities of 53 and 72 feet per second. The combustor inlet conditions and the flash duration of the light source used for each inlet-air condition are presented in the following table. With these flash durations, the lengths of the balsa-dust traces were sufficient for satisfactory interpretation of the photographs under the existing conditions.

Air flow, lb/(sec)(sq ft)	Inlet-air pressure, in. Hg abs	Inlet-air temperature, °F	Reference velocity, ft/sec	Flash duration μsec
1.0	30	90	26	220
2.0	29	95	53	190
2.5	27	85	72	160

When the combustor operating conditions had been established, the room was darkened, the balsa dust injected, the camera shutter opened, the flash tube fired, and the shutter closed. From six to eight photographs were taken of balsa-dust traces in each of a number of longitudinal and cross-sectional planes (fig. 4) for each operating condition in order to check for variation in the air-flow patterns with time.

RESULTS AND DISCUSSION

Photographs of air-flow patterns in the one-sixth-sector, transparent combustor are shown in figures 5 to 8. Flow patterns are presented for both the longitudinal and cross-sectional planes (fig. 4). In the photographs, the narrow ends of the balsa-dust traces point in the direction of the local air flow. The relative lengths of the individual traces are approximate indications of the components of the local velocities in the plane of the photograph. For easier visualization, several sketches of the flow patterns were prepared from the photographs and are presented in figures 6 to 8. The arrows of the sketches point in the direction of the local flow. The arrows are not proportioned in length to indicate relative local velocities but serve principally to indicate the general trends of the flow patterns at the particular stations.

Primary-Zone Flow Patterns

Examples of the flow patterns at cross-sectional planes 1-1 to 4-4 (see fig. 4) in the combustor primary-zone region are shown in figure 5. The photographs were selected primarily for clarity of reproduction. Examination of a number of such photographs indicated that there was no apparent stable-flow pattern at planes 1-1, 3-3, and 4-4 at any of the velocities investigated. There was a definite tendency towards the formation of vortices such as shown in figures 5(a), (c), and (d). However, the location, size, and number of these vortices at a given plane appeared to vary appreciably with time. There was also a definite tendency towards the formation of small recirculation zones between slots on the outer wall of the liner. Most of the photographs at plane 2-2 indicated a general flow towards the outer wall of the liner such as shown in the upper portion of figure 5(b).

Photographs of the upstream region of the liner at all longitudinal planes indicated a low-velocity recirculation region between the fuel manifold and plane 1-1. An example of the flow pattern at plane M-M (see fig. 4) is presented in figure 6; a sketch of the flow pattern prepared from this photograph is included. The size and the location of this recirculation region varied somewhat with time. There appeared to be no pronounced effect of velocity on the flow pattern. The recirculation appears to be the result of the high-velocity air jets issuing from the first set of slots on the inner wall of the liner. A low-velocity sheltered zone such as would be required for stable combustion at low-inlet pressures is formed. The strength of the recirculation or reverse flow was appreciably less than that found for the tubular combustor in reference 3. This might be expected since there are no large impinging air jets that would promote recirculation such as existed in the tubular combustor.

Secondary-Zone Flow Patterns

Photographs at cross-sectional planes 5-5 and 6-6 (see fig. 4) indicate well-defined flow patterns of two general types. Examples of the photographs and sketches of the corresponding flow patterns obtained in the secondary zone at these planes are presented in figure 7. There was no apparent effect of combustor reference velocity on the flow patterns at these planes. The principal difference between types I and II of figure 7 is the relative size of the swirls associated with the center pair of slots on the inner wall of the combustor.

Examples of photographs and flow-pattern sketches for the longitudinal planes J-J and M-M are presented in figure 8. The relative penetration from the inner and outer walls varied somewhat with time at each plane. However, the majority of the photographs exhibited over-all trends of flow patterns at these planes that are similar to those shown.

As is evident from the photographs and sketches of the flow patterns in the cross-sectional planes, there are large-scale circulatory air currents in the secondary region. These circulatory currents originate from the three pairs of slots on the inner wall of the liner and end in the low-pressure regions between these pairs of slots. The combination of this circulatory motion and the liner axial velocity results in contrarotating spiral currents of air passing through the liner secondary region. The air from the primary zone is forced into the regions between the highly penetrating sheets of air issuing from the pairs of slots on the inner wall.

From examination of a number of photographs, it was evident that the effective penetration of the air from the two outboard sets of slots on the inner wall of the liner was greater than that from the center pair of slots. This could be attributed to side-wall effects, since only one side of the air sheets issuing from the outboard slots was subject to shear forces from the primary-zone air currents.

Application of Flow-Pattern Studies to Combustor Design

The application of cold-flow pattern studies to combustion design is subject to the question of whether flow patterns without flame bear any relation to patterns with flame. An investigation of a single tubular combustor (ref. 3) indicates that similar patterns are obtained with and without combustion, although there is a shift in the location of the starting point of reverse flow. Accordingly, the interpretation of the cold-flow balsa-dust photographs is tentatively based on the assumption that they are representative of patterns that exist during combustion.

The existence of alternate longitudinal fuel-rich and air-rich regions during combustion is hypothesized in reference 2 as a possible reason for the improved performance obtained with the "slot-type" combustor design. Such a pattern would have been indicated in the cross-sectional-plane photographs by the appearance of well-defined individual jets of air issuing from the various slots in the primary-zone liner wall and penetrating well into the primary zone. In the balsa-dust photographs, however, the identity of the individual air jets issuing from primary-zone slots was lost within a short distance of the wall. Although it is possible that alternate fuel-rich and air-rich regions could have existed over the portions of the primary zone where the individual air jets had lost their identity, such regions could not be distinguished in the balsa-dust photographs.

The photographs along the longitudinal plane gave a clear picture of a low-velocity recirculation region near the fuel manifold. This recirculation region appeared to result from the high-velocity jets of air issuing from the first row of closely spaced slots on the inner wall of the liner. Consequently, it would appear that the size of the recirculation zone for this particular combustor might be controlled to some extent by the axial position of the first row of slots on the inner wall.

The importance of slot pitch in the control of the combustor outlet-temperature distribution was recognized and investigated in reference 2. Both the length and the pitch of slots in the secondary zone were changed in order to produce the desired outlet-temperature profile. The effect of slot pitch on flow patterns in the combustor can be inferred from a comparison of the flow patterns shown in figures 5(b) and 7(c) and (d). Examination of many photographs taken along the cross-sectional and longitudinal planes of the upstream portion of the primary zone indicated that the air jets from the first row of closely spaced slots (small pitch) on the inner wall of the liner mix with each other within a short distance from the wall. The result is a general flow of air from the inner wall to the outer wall of the liner at plane 2-2 as shown in figure 5(b). The air approaching such a row of slots is pushed towards the outer wall of the liner. There is apparently little mixing of the approaching air stream with the air entering from the slots. The flow patterns to be associated with widely spaced slots (large pitch) are shown in figures 7(c) and (d). The large pitch of the slots on the inner wall of the liner appeared to produce large-scale swirls. The high penetration of the air sheets issuing from the pairs of slots on the inner wall also results in a longitudinal partitioning of gases in the secondary zone as discussed in reference 2. The combination of the swirl and the high penetration of the air jets from the inner wall of the liner using widely spaced slots should result in a greater degree of mixing than would be expected from the use of closely spaced slots. Thus if a row of closely spaced slots were used on the inner wall of the combustor secondary zone, the hot gases leaving the primary zone would be pushed to the outer wall. The result would be a shift in the high-temperature region to the outer wall and a steep temperature profile. On the other hand, the improved mixing obtained with the widely spaced slots on the inner wall of the combustor secondary zone should result in a flatter temperature profile. The combustor outlet-temperature profile data of reference 2 are in general agreement with these suggested trends.

The influence of side walls on penetration and circulation currents previously noted is a possible reason for the well-known difficulty in applying outlet-temperature profile data from sector annular combustors to the prediction of outlet-temperature profiles in the full annulus (ref. 2). The existence of the circulation currents also emphasizes the difficulties to be encountered in the use of penetration and spreading data from jets directed into air streams in the design of the secondary zone of annular combustors.

CONCLUDING REMARKS

The photographic investigation of cold-flow air patterns in the slot-type annular combustor indicated several definite trends in flow pattern resulting from the use of this particular type of liner air-entry configuration. Photographs along the longitudinal plane of the combustor primary zone indicated the presence of a slowly rotating recirculation zone in the vicinity of the fuel manifold. The recirculation zone appeared to result from the jets issuing from the first row of closely spaced slots on the inner wall of the liner. The strength of the reverse flow in this region was appreciably less than that found for a tubular combustor during a previous investigation. Photographs along the cross-sectional plane of the combustor secondary zone disclosed large-scale air swirls and a longitudinal partitioning of the air leaving the primary zone. The swirls appear to result from the use of wide spacing of the air-entry slots on the inner wall of the secondary zone. The side walls of the one-quarter-sector combustor appeared to have a pronounced effect on the flow patterns.

Comparison of the combustor flow patterns indicated the effect of slot spacing on air-flow pattern. The photographs indicated that the use of closely spaced slots in the combustor secondary zone would result in less mixing and hence a steeper outlet-temperature profile during combustion, whereas, the use of widely spaced slots would result in greater mixing and a flatter temperature profile. Although this investigation was carried out at combustor reference velocities below those normally encountered in engine operation, there appeared to be no significant effect of reference velocity on the flow patterns.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 28, 1954

APPENDIX - PHOTOGRAPHIC TECHNIQUES

Balsa-dust injection. - Balsa-dust flow tracers were injected into the air stream through two tubes located approximately 4 inches upstream of the fuel manifold (see fig. 3). In order to assure a sufficient dust density in the particular longitudinal plane to be photographed, the tubes were alined with that plane and positioned so as to inject at the centers of the inner and outer annuli. For the cross-sectional plane photographs, the tubes were positioned at the centerline of the fuel manifold and spaced approximately 6 inches apart.

The method of balsa-dust preparation and injection described in reference 4 was used with one modification: the balsa dust was blown from a container into the combustor air stream under pressure of oil-pumped nitrogen instead of compressed air. In the investigation described in reference 3, it was found that moisture in the compressed air caused an opaque film of dust to deposit on the combustor walls.

Camera and light source. - Photographs of the balsa-dust flow tracers were obtained with a 5- by 7-inch bellows camera, equipped with an f/4.5, 190-millimeter focal length lens. Illumination of the balsa-dust particles was provided by a gas-filled electronic flash tube, 7/16 inch in diameter and $24\frac{1}{2}$ inches in length. The flash duration of the light source could be varied from approximately 135 to 990 microseconds by appropriate combination of the parallel condensers shown in the power-supply circuit diagram (fig. 9). The flash tube was mounted in a box having a slit approximately 1/4 inch wide. An aluminum-foil reflector was mounted behind the flash tube. The use of a slit source of light allowed only the dust particles in a narrow plane to be photographed. The camera positions and lighting arrangements used in obtaining the reported data are shown in figure 3.

For the photographs of plane J-J, the camera back was tilted to obtain simultaneous focusing on small tabs that were mounted inside the liner and coincident with plane J-J (e.g., see figs. 5 and 8(a)). For photographs of the remaining longitudinal planes, the light source was positioned at the desired plane and, with no change in the camera back, the camera was focused on two grids attached to the side of the adjustable slit of the light source (see fig. 3(a)). To compensate for the slight divergence of the longitudinal planes of focus (see fig. 4), the camera was rotated about a vertical axis until both grids were in focus.

For the cross-sectional-plane photographs, use was made of the window and mirror downstream of the combustor (see fig. 3(b)). The camera was directed into the window and the light source was mounted vertically and at right angles to the main axis of the combustor. To eliminate light losses by reflection from the side walls, the light source was located on the convex side of the combustor. The planes chosen to be photographed contained easily recognizable features, such as a row of cooling louvres, upon which the camera could readily be focused. For this series of photographs, the camera was not tilted and therefore the camera back did not have to be tilted.

Film. - A special high-speed orthochromatic film was used in all tests. This film was used because the flash-tube discharge was distinctly blue and orthochromatic film has its highest sensitivity in the blue range of the spectrum. To obtain adequate resolution of the dust traces on this film, it was necessary to maintain a maximum nominal lens opening of f/8.0.

Reproduction. - For improved clarity of reproduction, negative prints (dark traces on a light background) were obtained by making positive films from the original negative films. Emulsion-to-emulsion contact printing was used in all steps to avoid loss of definition of the balsa-dust tracers.

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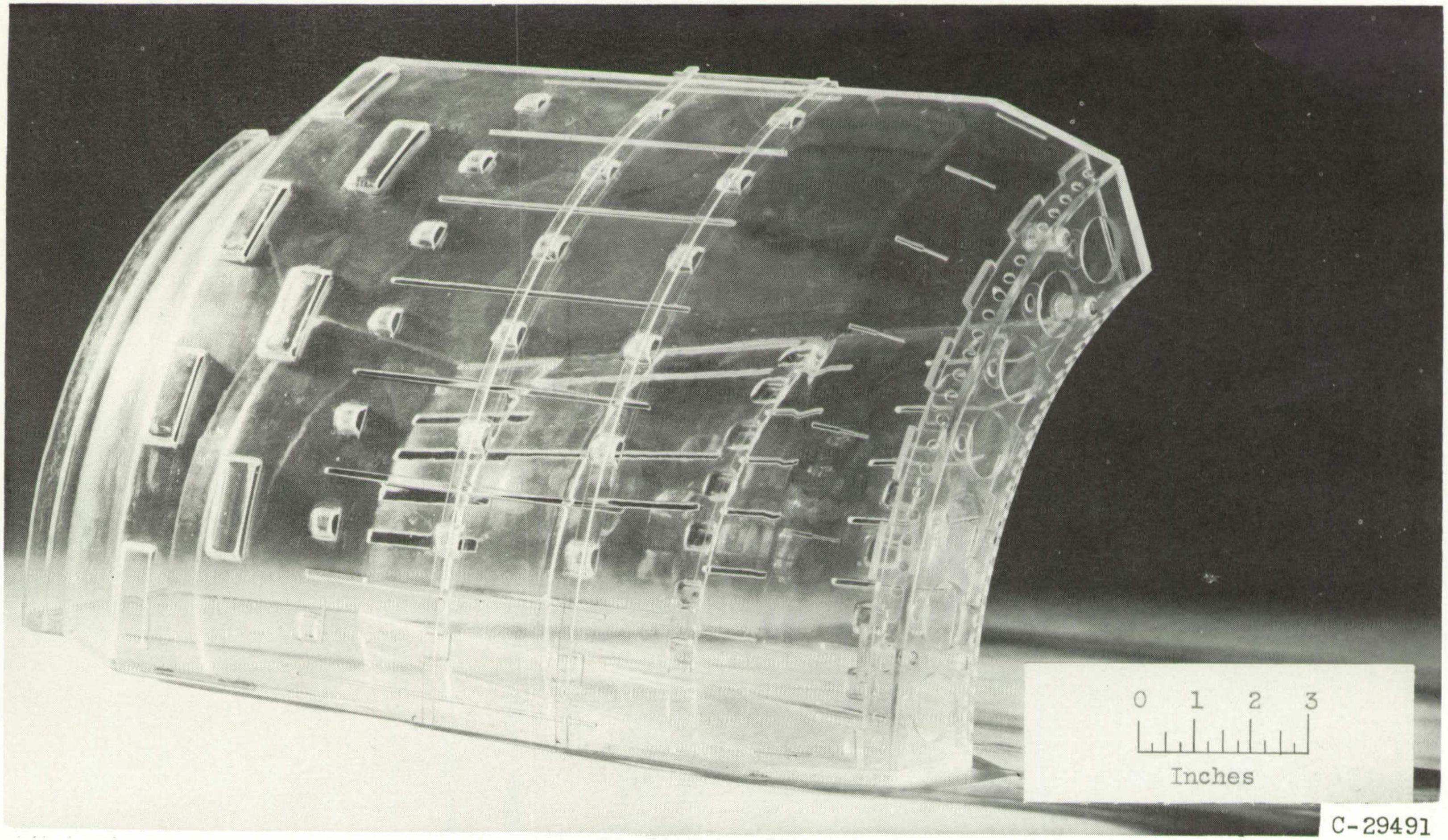
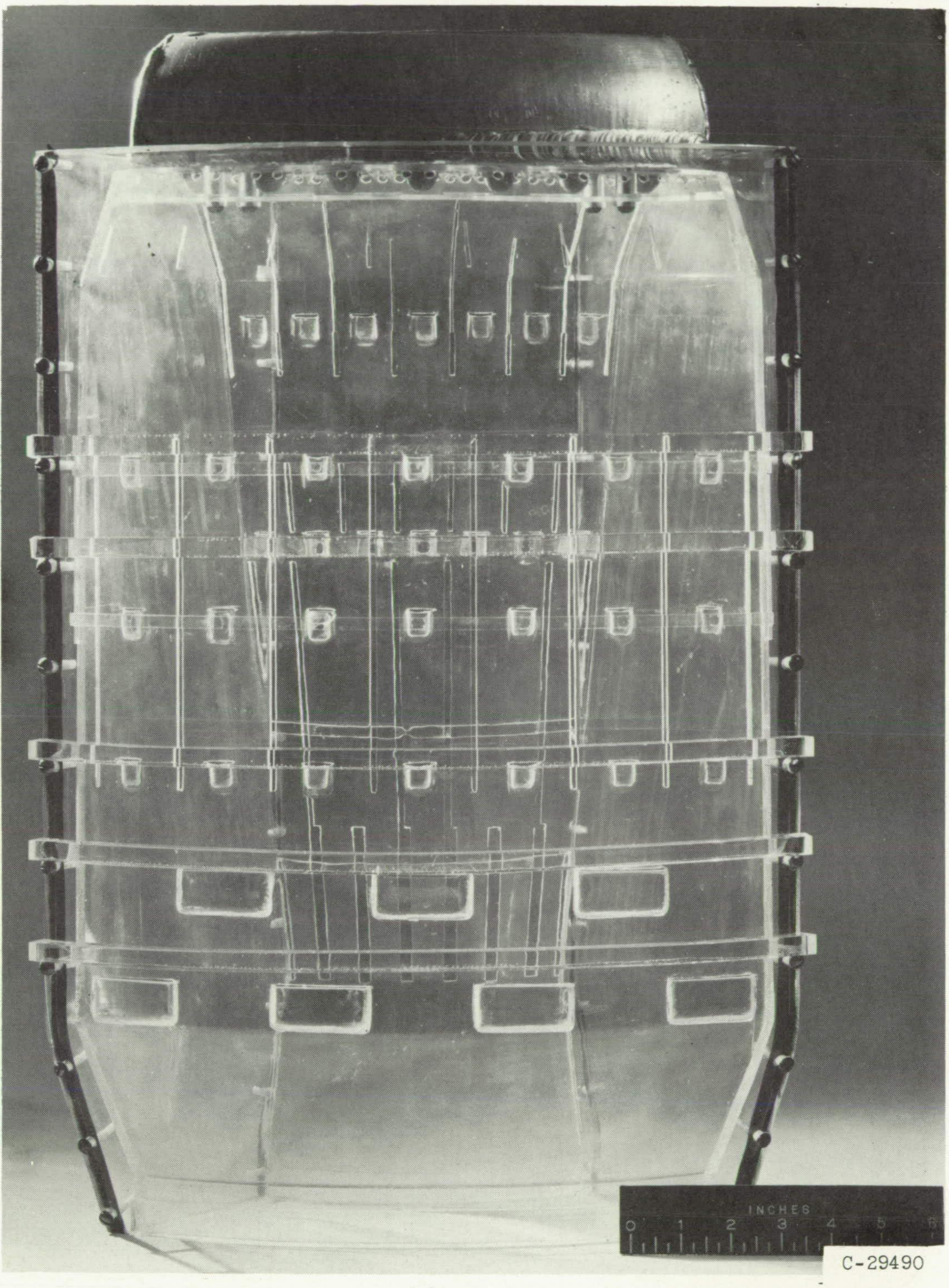
4. Younger, George G., Gabriel, David S., and Mickelsen, William R.: Experimental Study of Isothermal Wake-Flow Characteristics of Various Flame-Holder Shapes. NACA RM E51K07, 1952.



(a) Liner.

Figure 1. - Transparent model of one-sixth sector annular turbojet-engine combustor.



(b) Assembly.

Figure 1. - Concluded. Transparent model of one-sixth sector annular turbojet-engine combustor.

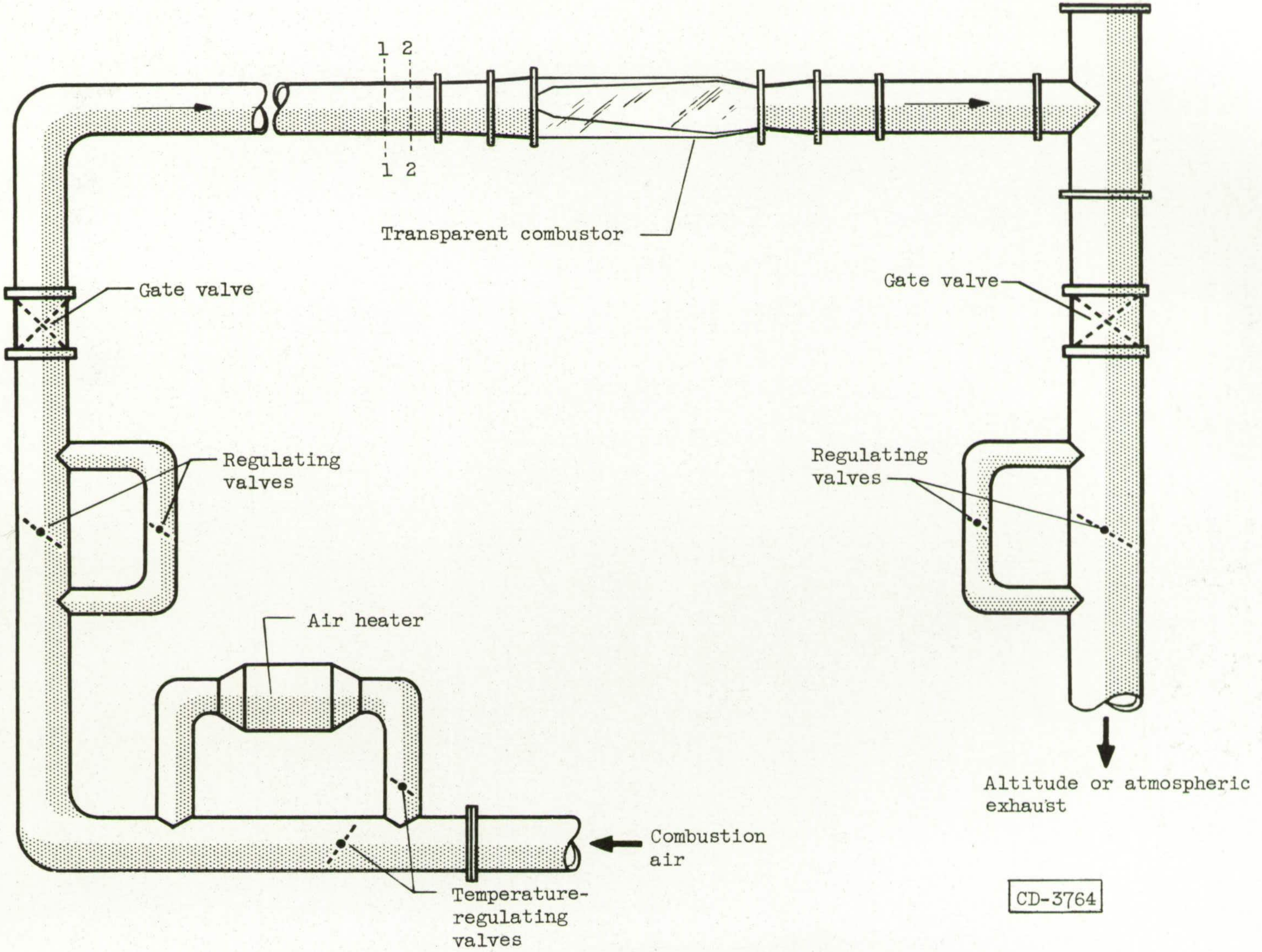
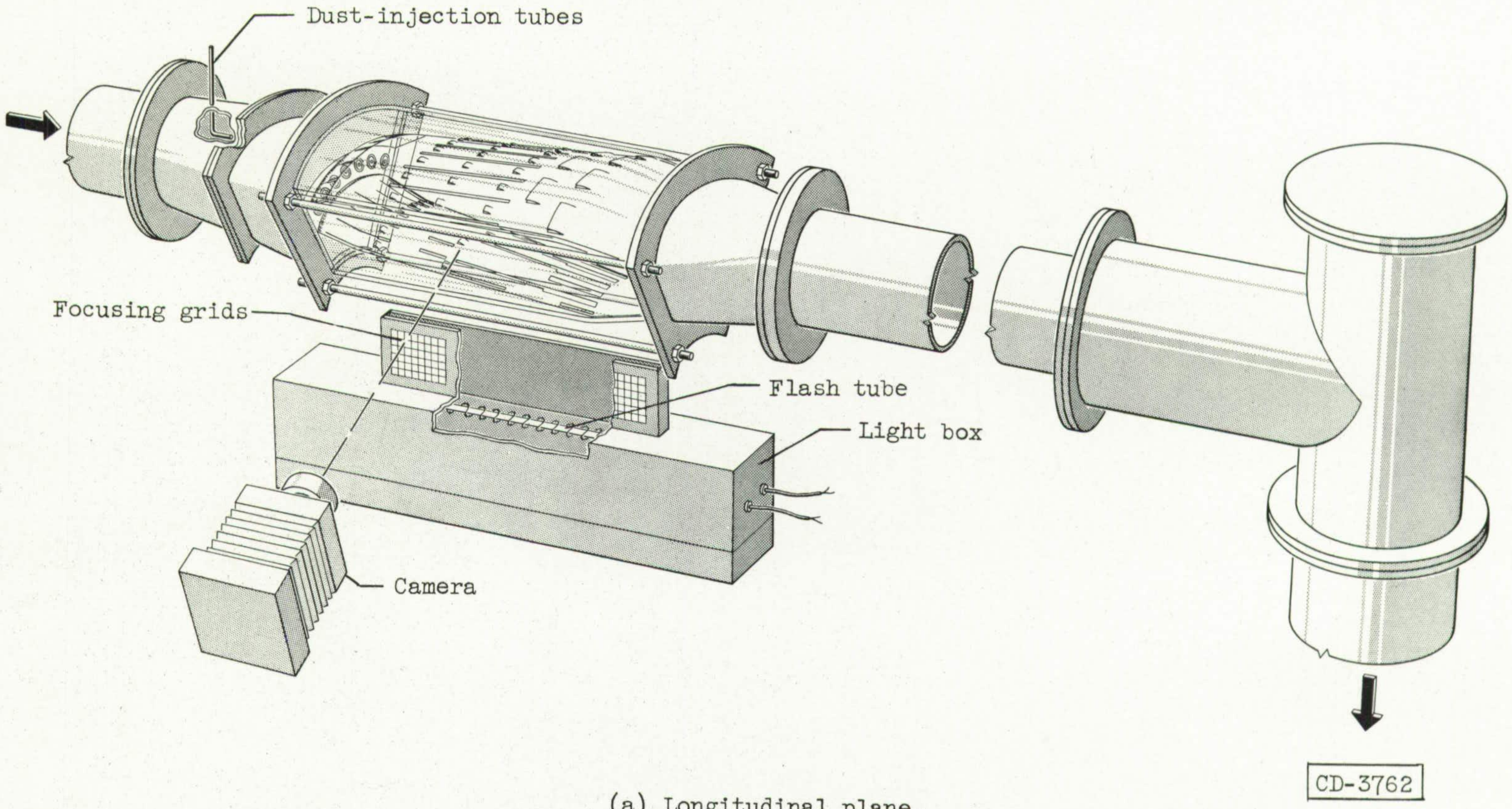
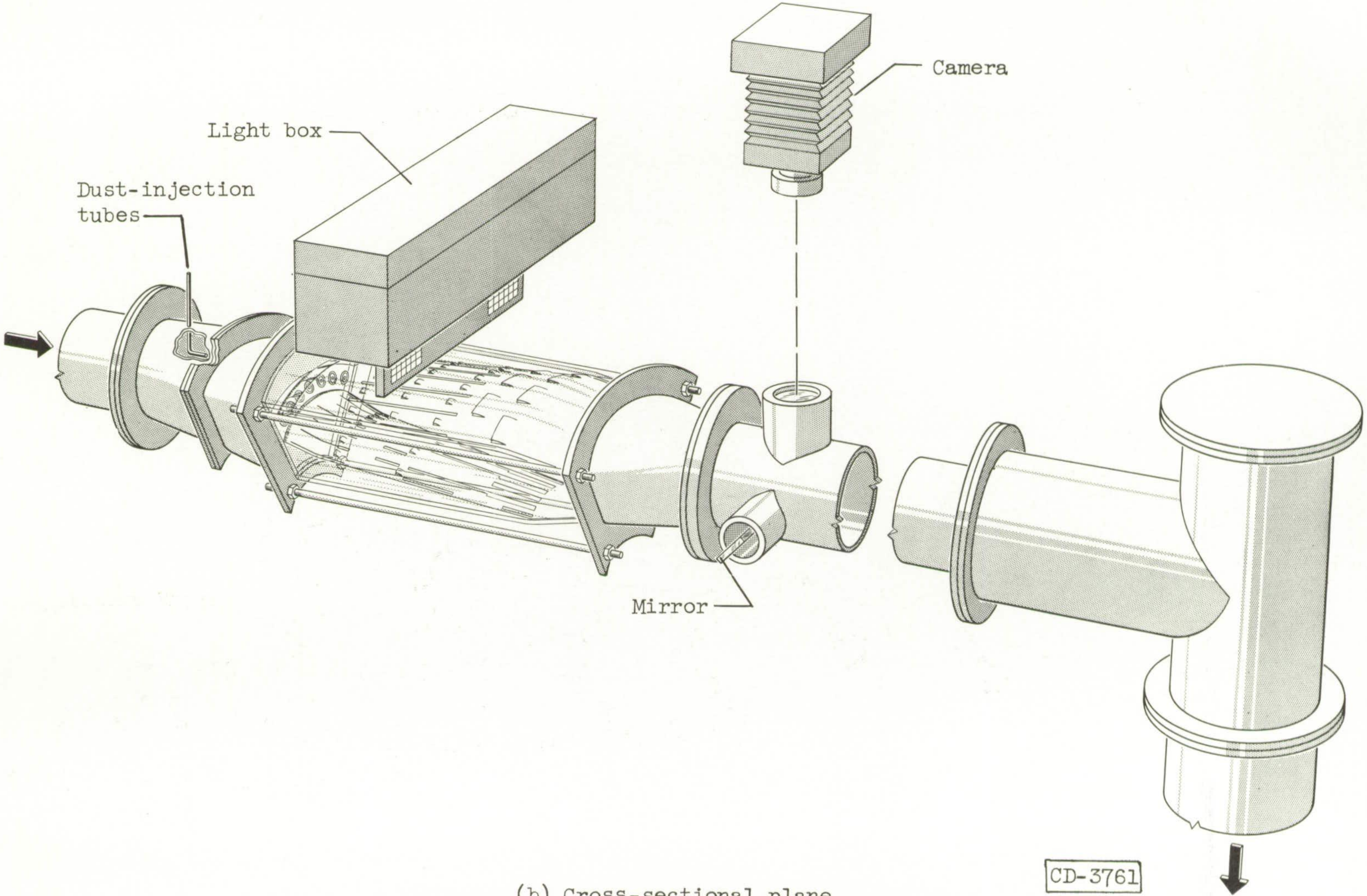


Figure 2. - Schematic diagram of cold-flow combustor installation.



(a) Longitudinal plane.

Figure 3. - Camera and light source positions used in cold-flow combustor photographic studies.



(b) Cross-sectional plane.

Figure 3. - Concluded. Camera and light source positions used in cold-flow combustor photographic studies

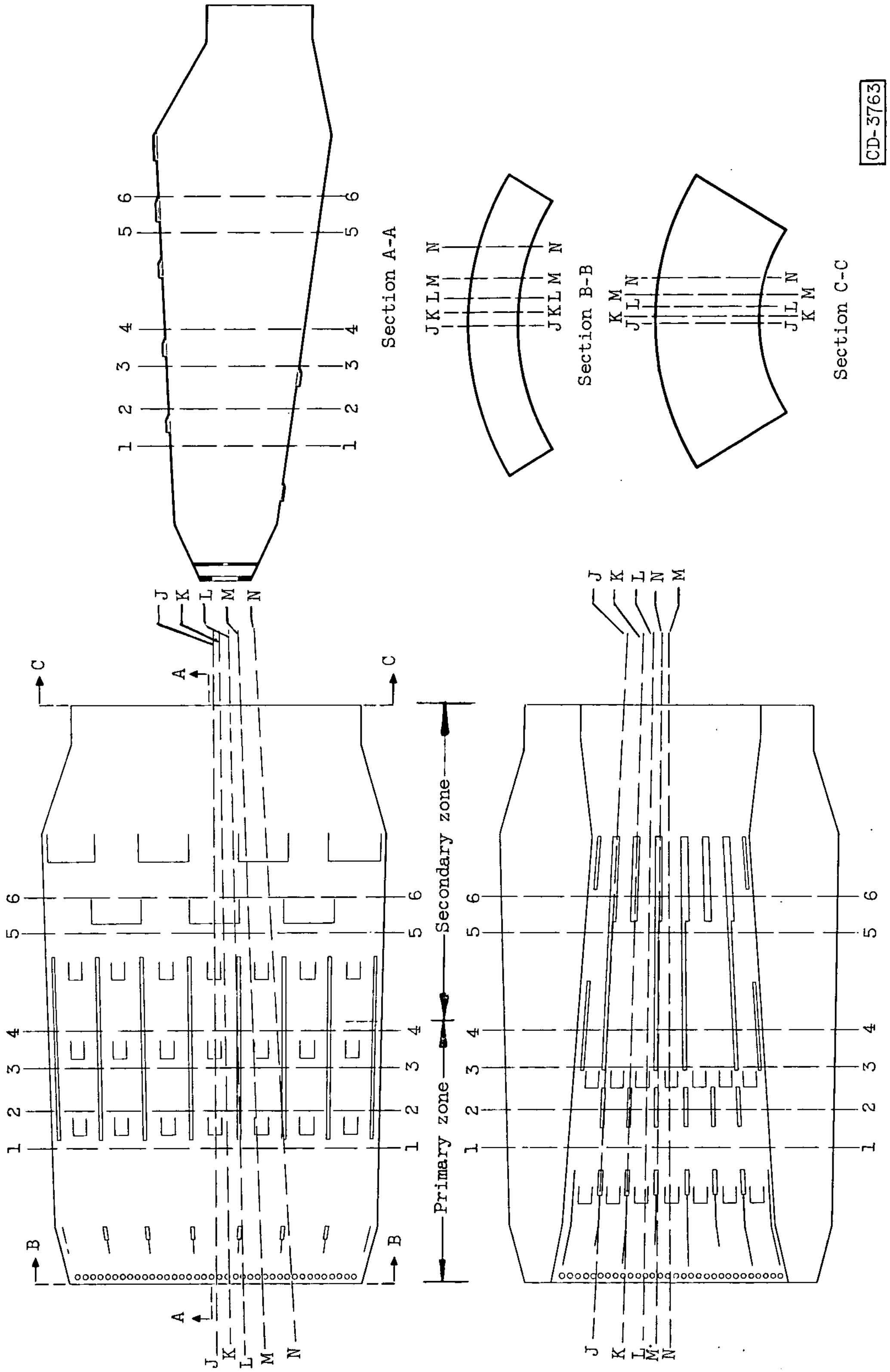
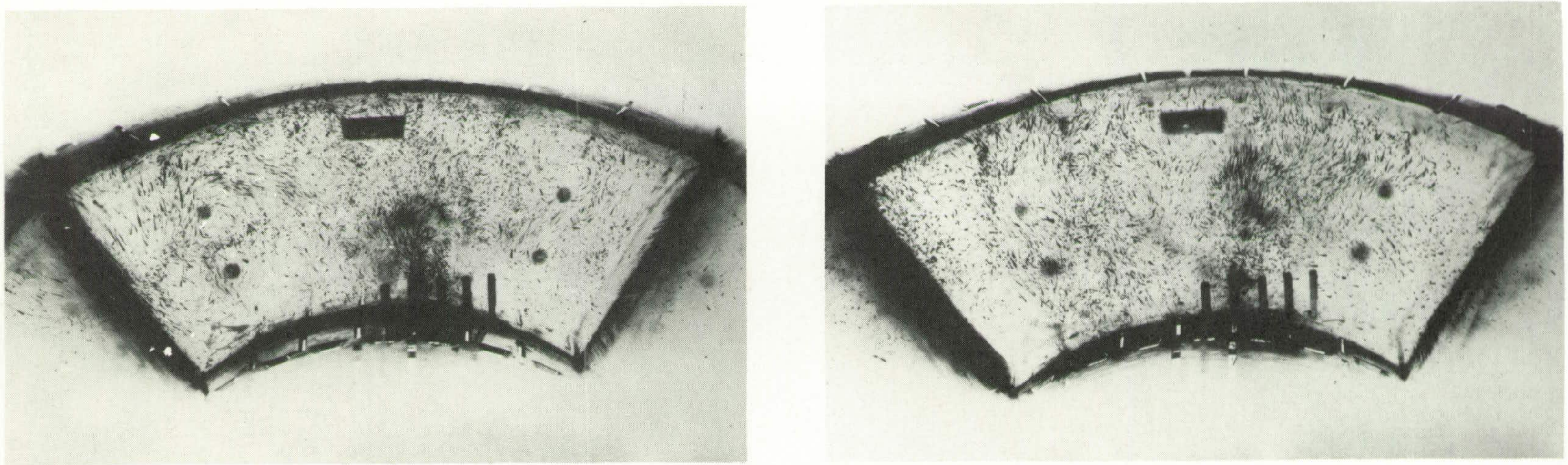
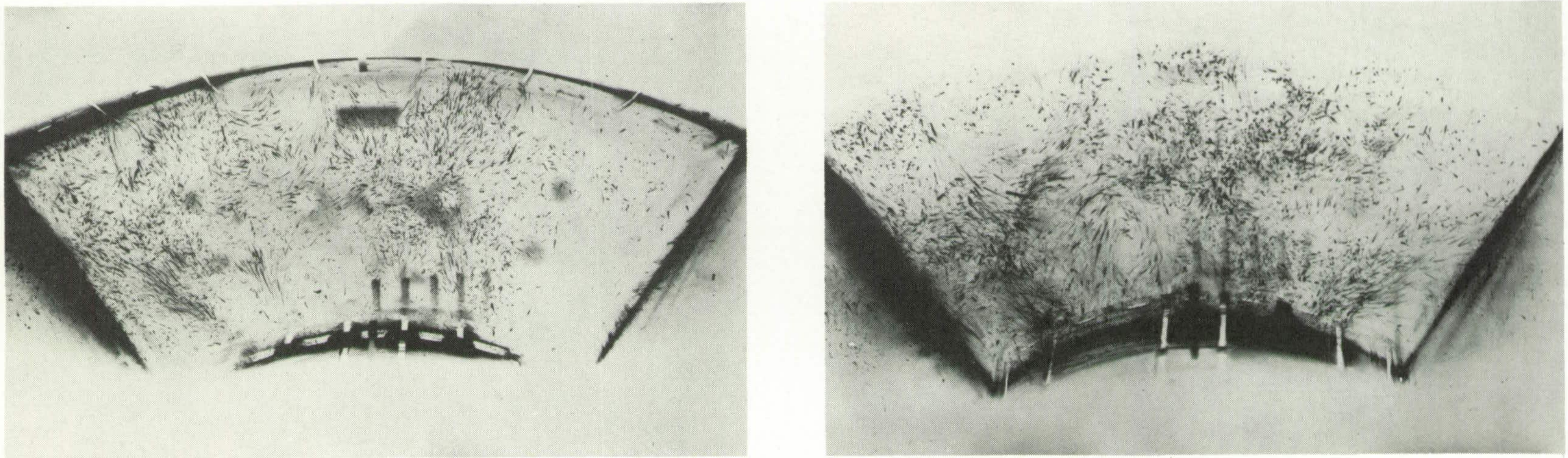


Figure 4. - Location of longitudinal and cross-sectional photographic planes.



(a) Plane 1-1.

(b) Plane 2-2.



(c) Plane 3-3.

(d) Plane 4-4.

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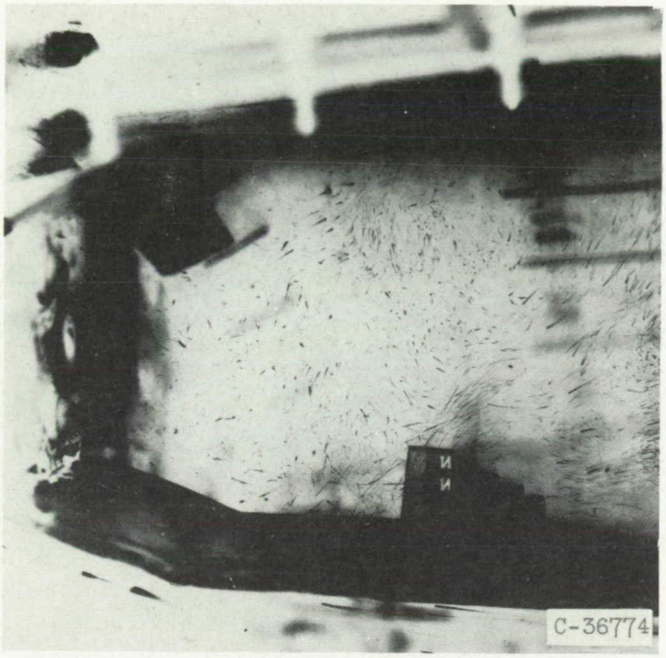
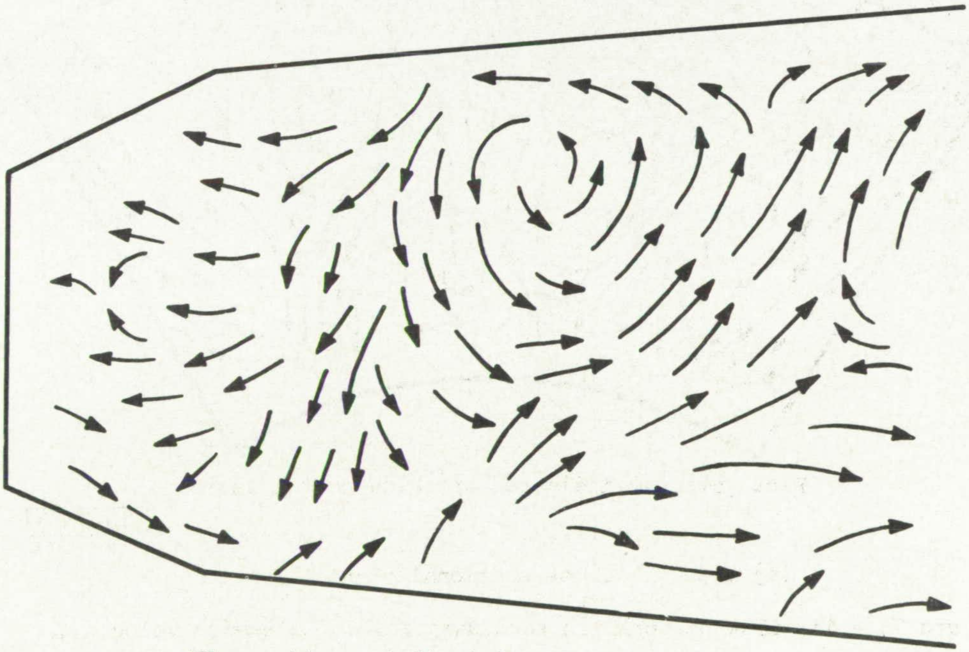
Figure 5. - Cross-sectional-plane photographs of air-flow patterns in primary zone of transparent combustor. Patterns indicated by balsa-dust tracers. Reference velocity, 26 feet per second.

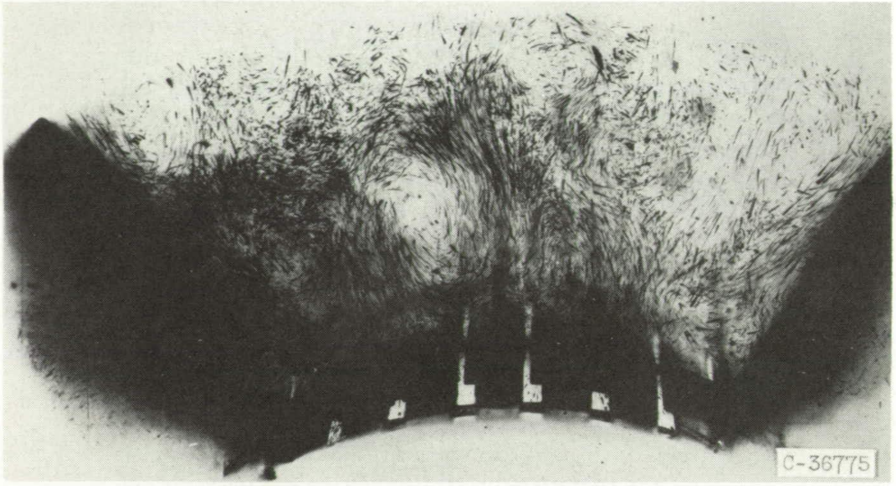


Balsa-dust tracers

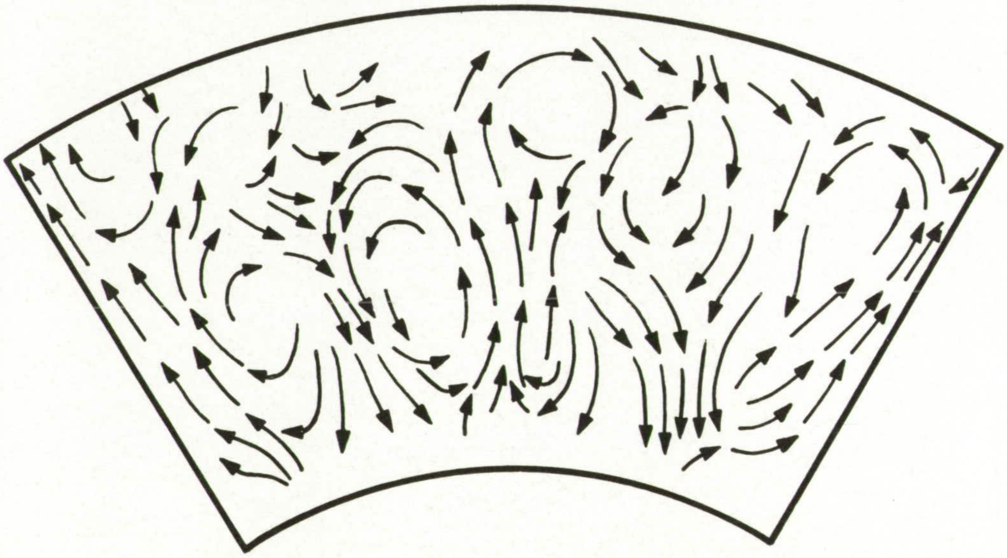


Flow patterns indicated by balsa-dust tracers

Figure 6. - Air-flow patterns in primary zone along longitudinal plane M-M. Reference velocity, 26 feet per second.



Balsa-dust tracers

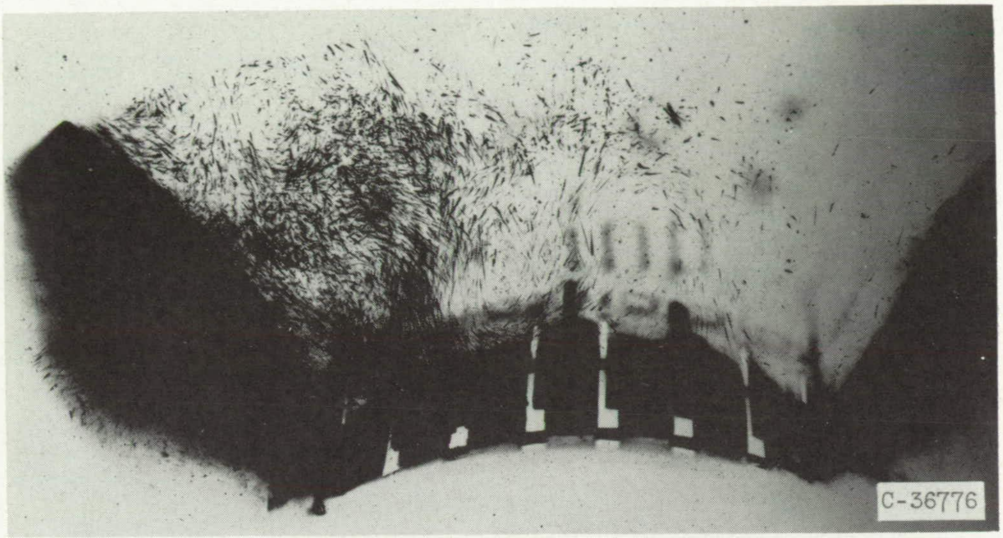


Flow patterns indicated by balsa-dust tracers.

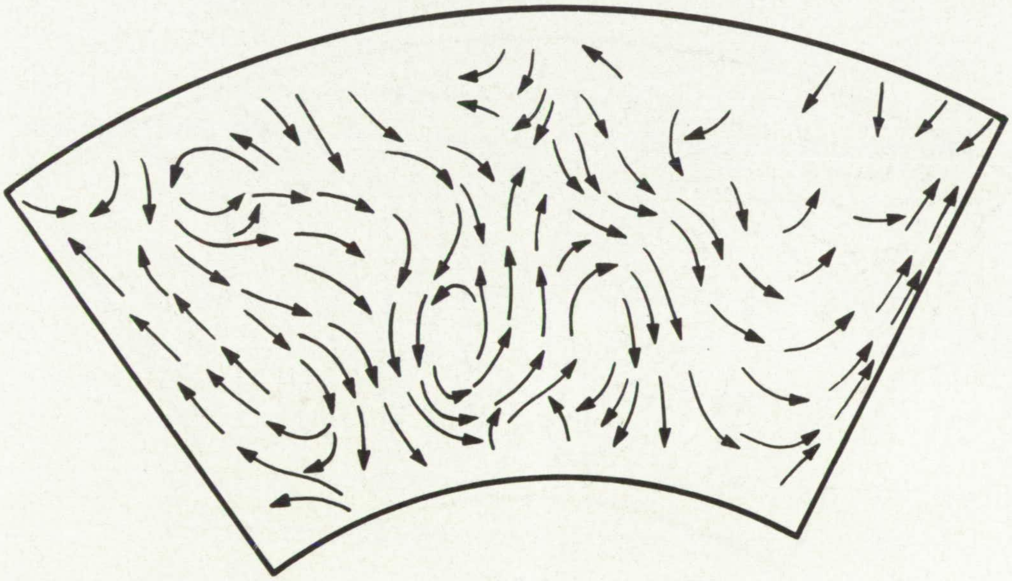
CD-3770

(a) Type I. Cross-sectional plane 5-5.

Figure 7. - Air-flow patterns in secondary zone. Reference velocity, 26 feet per second.



Balsa-dust tracers

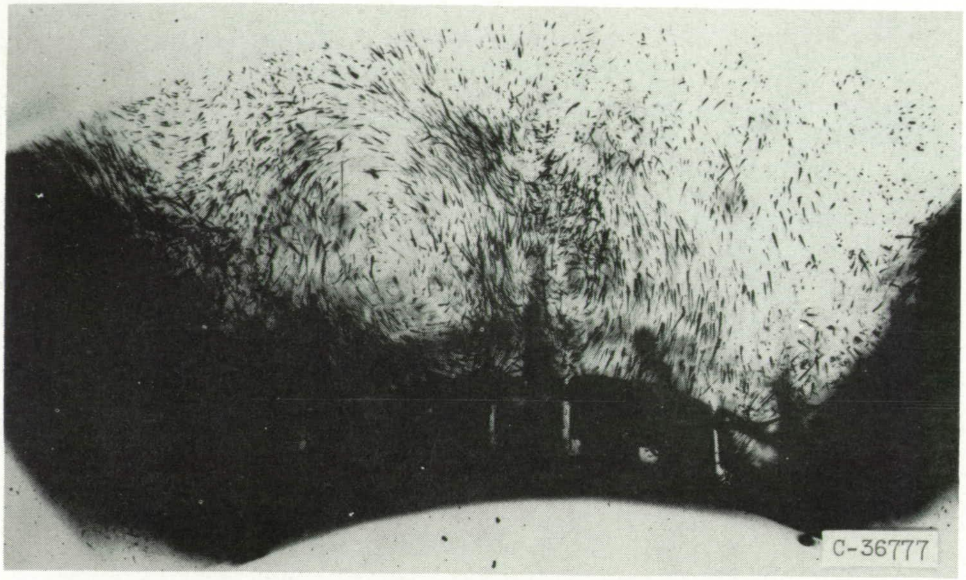


Flow patterns indicated by balsa-dust tracers

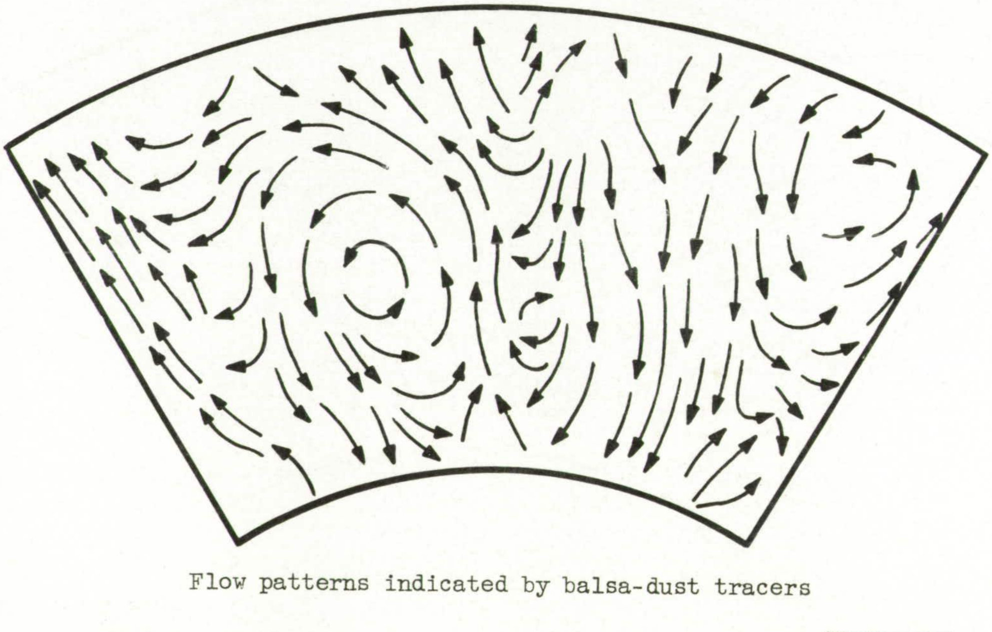
CD-3769

(b) Type II. Cross-sectional plane 5-5.

Figure 7. - Continued. Air-flow patterns in secondary zone. Reference velocity, 26 feet per second.



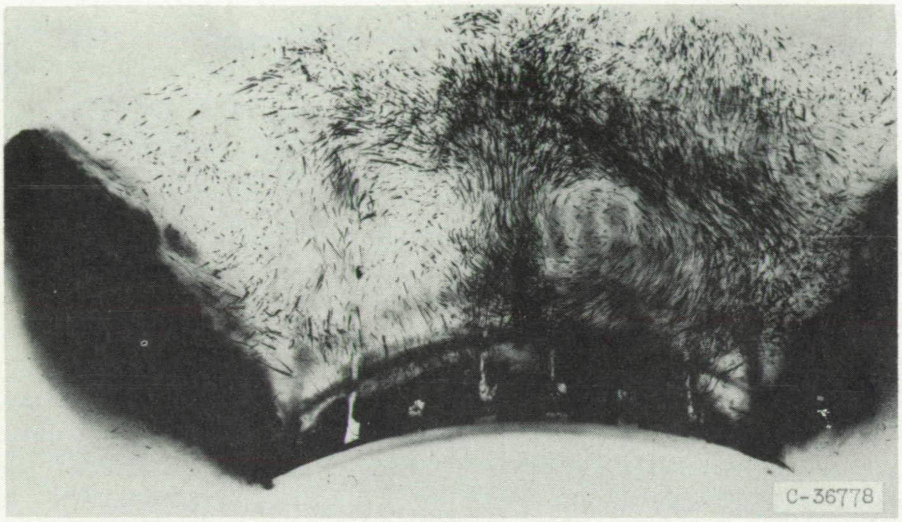
Balsa-dust tracers



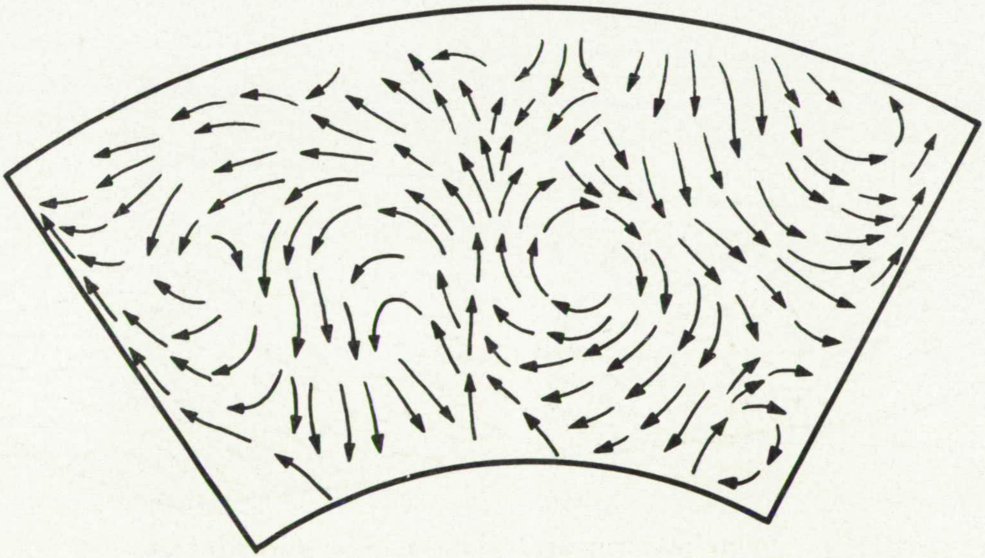
Flow patterns indicated by balsa-dust tracers

(c) Type I. Cross-sectional plane 6-6.

Figure 7. - Continued. Air-flow patterns in secondary zone. Reference velocity, 26 feet per second.



Balsa-dust tracers



Flow patterns indicated by balsa-dust tracers

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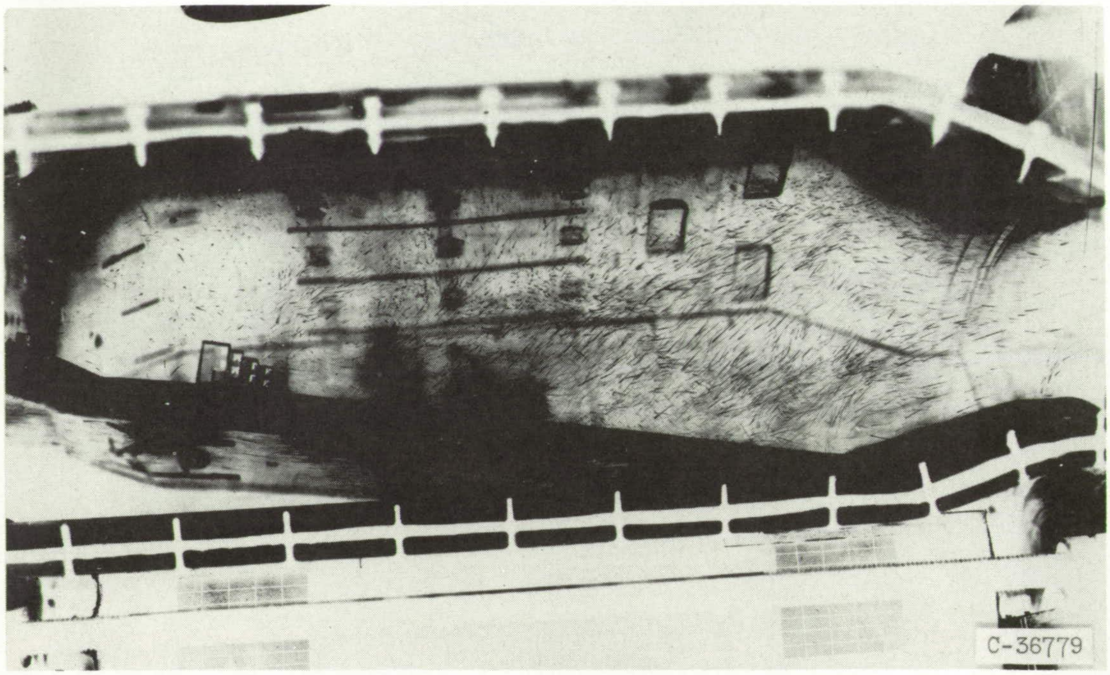
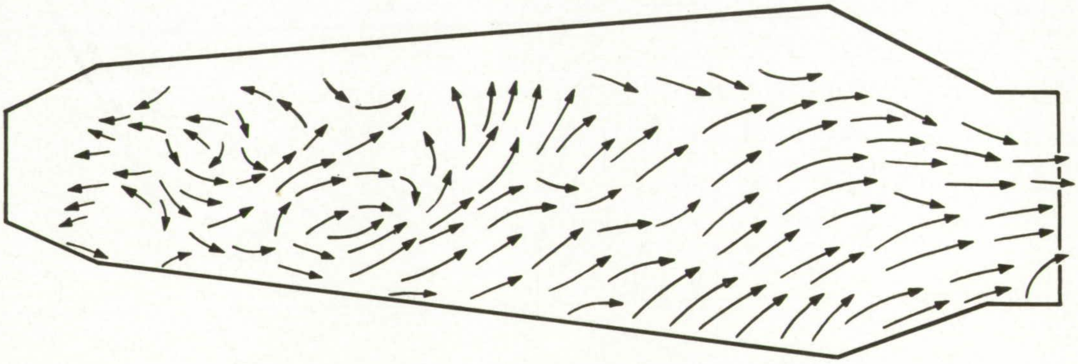
(d) Type II. Cross-sectional plane 6-6.

Figure 7. - Concluded. Air-flow patterns in secondary zone. Reference velocity, 26 feet per second.



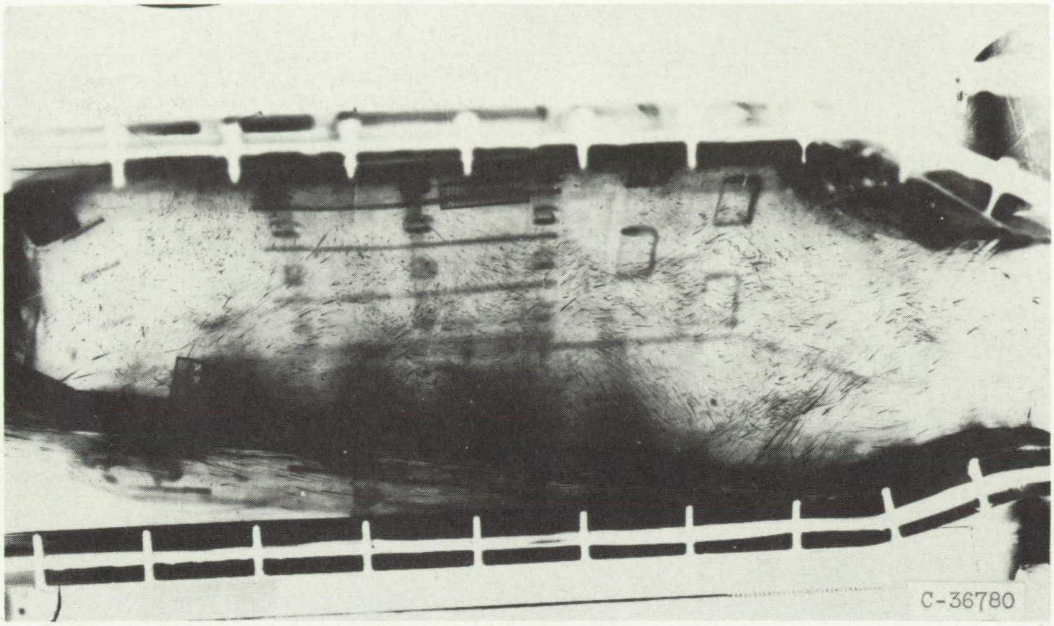
Balsa-dust tracers



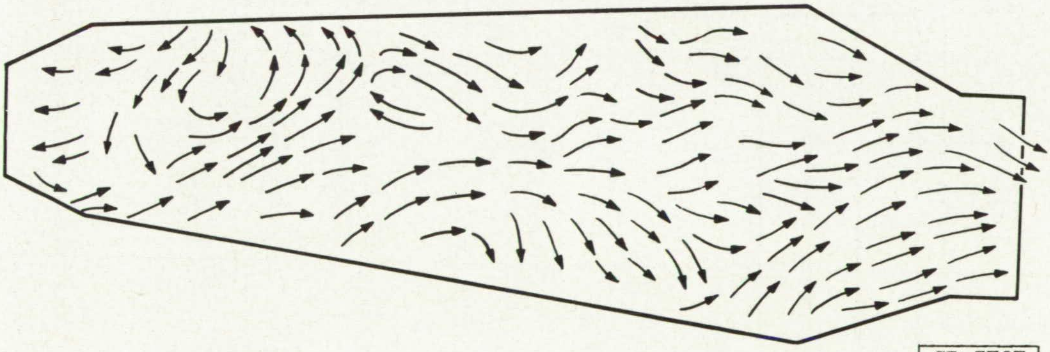
Flow patterns indicated by balsa-dust tracers

(a) Plane J-J.

Figure 8. - Air-flow patterns along two longitudinal planes. Reference velocity, 26 feet per second.



Balsa-dust tracers



Flow patterns indicated by balsa-dust tracers

(b) Plane M-M.

Figure 8. - Concluded. Air-flow patterns along two longitudinal planes. Reference velocity, 26 feet per second.

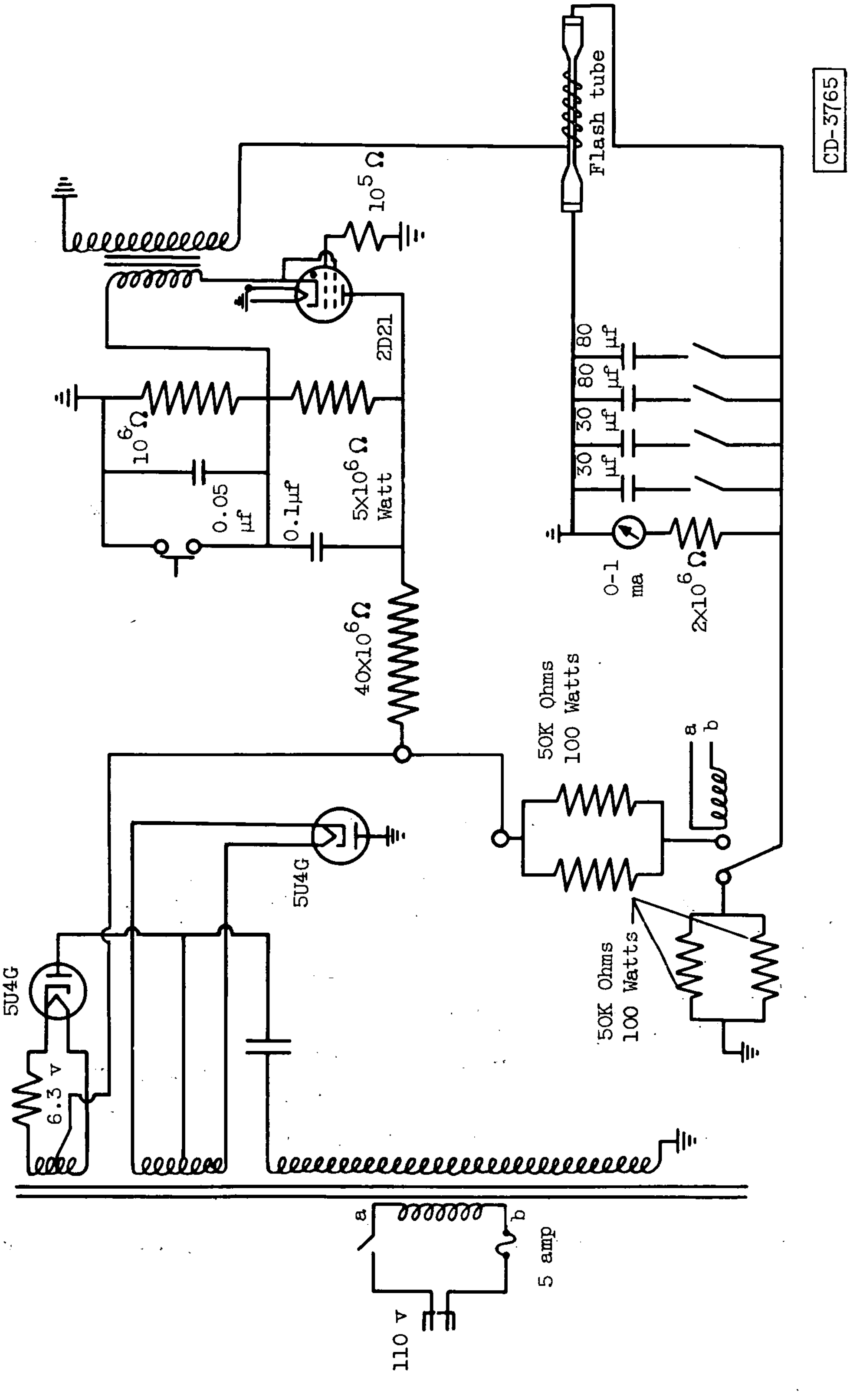


Figure 9. - Circuit diagram of flash tube, 2000-volt power supply.