# EXPERIMENTS CONCERNING THE OCCURRENCE AND MECHANISM OF HIGH-FREQUENCY COMBUSTION INSTABILITY

Thesis by

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## ABSTRACT

The phenomenon of screeching combustion was examined experimentally with particular reference to the significance of the time lag proposed by Rogers and Marble.

This investigation was conducted in a 1- x 4-inch rectangular cross-section water-cooled combustor in which was burned a premixed air - fuel mixture. This combustor contained a 70 °/o blockage solid V-wedge flameholder.

Vortices were generated at the flameholder lips during smooth combustion by impinging a shock wave on the flamefront. These vortices were compared with those generated during screeching combustion and found to be similar to them in all major respects. Thus the common assumption that vortices are generated by the action of the oscillating velocity is a sound one.

The fact that screech excitation occurs in the shear layers immediately downstream of the flameholders was demonstrated by injection of air into this region. Such injection was found to suppress the tendency of the combustor to screech.

By comparison of observations of the screech limit with ignition time delay data obtained from bluff-body flameholding studies it was shown that the mechanism of screech excitation is indeed controlled by a characteristic time. A procedure, based on this result, was developed for determining in advance the behavior of the screech limit in a family of geometrically similar combustors under variations of fuel type and inlet temperature.

TABLE OF CONTENTS

## NOMENCLATURE

| | |
|---|---|
| $D$ | Mean vortex diameter, in. |
| $\ell$ | A characteristic dimension, in. |
| $M_L$ | Average Mach number at flameholder lip; calculated by one-dimensional gas dynamics for expansion from known stagnation conditions, dimensionless. |
| $P$ | Pressure, psi.<br>Also used to indicate the location of a pressure loop. |
| $t$ | Time, $\mu$sec. |
| $T$ | Period of a periodic oscillation, $\mu$sec. |
| $T_L$ | Static temperature of combustible mixture at the flameholder lip, $^oR$. |
| $T_t$ | Stagnation temperature of combustible mixture at entrance to the combustion chamber, $^oR$ |
| $w_a$ | Primary air mass flow rate, lb/sec. |
| $w_i$ | Injection air mass flow rate, lb/sec. |
| $x$ | Axial distance of vortex "center" from near face of flameholder, inches. |
| $\phi$ | Overall equivalence ratio, dimensionless: the sum of individual equivalence ratios of each component of the fuel mixture. Each individual equivalence ratio is equal to the fuel - air ratio for the fuel component in question (as if no other components were present) divided by its stoichiometric value. |
| $\phi_H$ | Hydrogen (individual) equivalence ratio, dimensionless. |
| $\phi_s$ | Overall equivalence ratio at the lean screech limit, dimensionless. |
| $\tau$ | A time lag, msec. |
| $\tau_c$ | The screech characteristic time, msec. |
| $\tau_i$ | The ignition time delay of bluff-body flameholding, msec. |

# 1. INTRODUCTION

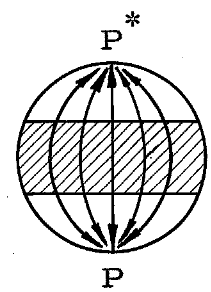
Screeching combustion, or screech, is a large amplitude, high-frequency, periodic combustion instability occurring in combustion chambers utilizing bluff-body flameholders. Screech is characterized by the suddenness of its commencement, marked shortening of the flame zone, high rates of heat transfer to the combustor walls, increased combustion efficiency, and the high-pitched screeching sound for which it is so aptly named. The ability of screech to destroy a combustor in a matter of seconds presents a serious problem to the combustor designer. He must learn how to eliminate screech, or better still, to control it so that the resulting increased combustion efficiency might be exploited.

Credit for the recognition of screech as a phenomenon distinct from other combustion instabilities has been extended to the Research Division of United Aircraft Corporation (1). It has since been studied by Rogers (2), Moore and Maslen (3), Kaskan and Noreen (4), Truman and Newton (5), Blackshear, et al (6), Rogers and Marble (1) and Elias (7).

Truman and Newton (5) studied screech in combustors of various sizes, of circular and rectangular cross-section, employing a variety of flameholders. They found that the frequency of screech in combustors of similar geometry varied inversely as the transverse dimension of the combustor, and was not affected by the longitudinal dimensions or variations in the fuel supply system. They properly concluded from this that screech was associated with transverse and/or radial modes of acoustic oscillation of the gases in the combustor -- modes characterized by oscillating velocities directed principally in planes perpendicular to the combustor axis. Particular modes (first, second, etc.) were assigned according to the value of the observed frequency of oscillation. This is a questionable procedure, owing to the numerical density of higher modes which have similar characteristic frequencies, and to the uncertainty in the effective speed of sound in this type combustor. It is true, however, that higher frequencies are associated with higher modes of oscillation. On this basis we may accept Truman and Newton's observation that the probability of occurrence of higher modes increases with increasing combustor cross-section. Frequencies of screech observed in this study ranged from 1000 to 3350 cps.

Other observations made by Truman and Newton include the following: (a) Blockage: Screech seldom occurred for blockages less than about 30 °/o. As blockage increased, the range of operating variables over which screech occurred also increased. Combustors with blockages greater than 80 °/o tended to screech over their entire range of operation. (b) Mode orientation: Configuration employing straight V-gutter flameholders screeched in modes such that the principal direction of gas motion was perpendicular to the flameholder. (c) Local fuel injection: In screech-prone combustors in which fuel was injected at the apex of a hollow V-gutter flameholder, screech continued to occur. If the fuel was injected at the lip of the flameholder, screech did not occur.

Blackshear, Rayle, and Tower (6) studied screech in a 6-inch diameter cylindrical combustor utilizing straight V-gutter and conical flameholders of 30 °/o and 46 °/o blockage. They established by means of pressure amplitude and phase shift surveys that the mode of oscillation of screech in this combustor was the first transverse mode. The directions of gas motion corresponding to this mode are shown qualitatively in Sketch A. Again it should be noted that the principal direction of gas motion is perpendicular to the flame holder (shaded in sketch). The frequency of screech in this mode of oscillation was 3300 cps. A low-frequency (490 cps) longitudinal mode was also observed in this combustor, but was considered to be excited independently of the screech mode. An axial survey of screech pressure amplitudes at the combustor wall exhibited a strong maximum at a point about six inches downstream of the flameholder. It was suggested that this maximum indicates the station at which screech excitation takes place. It was also observed that the combustion efficiency of this combustor increased from 35 °/o to 90-100 °/o as screech commenced.




Sketch A

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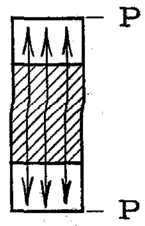
* P: Location of a pressure loop.

Kaskan and Noreen (4) studied screech in a combustor of 2- x 4-inch cross-section with a 3-inch-wide V-gutter flameholder parallel to the 2-inch wall. Extensive high-speed photographic studies showed that, during screech, vortices were shed from the flameholder lips in the familiar pattern of the Kármán vortex street. The vortices were found to be shed from each lip with the frequency of the pressure oscillation, 4000 cps in this case. The mode of oscillation was assigned from the observed frequency to be the first transverse mode, with gas motion perpendicular to the flameholder (Sketch B). A low-frequency (330 cps) longitudinal mode was observed in this combustor also.



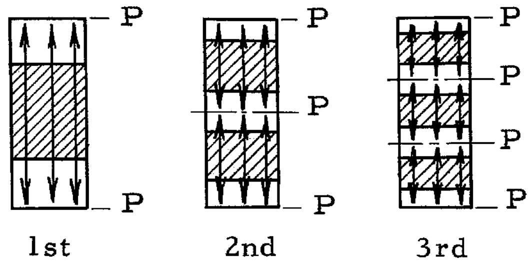

Sketch B

Kaskan and Noreen also studied the behavior of the screech limit, the boundary between regimes of smooth operation and screeching operation of the combustor. The fuel-air ratio at the screech limit was determined as a function of combustor inlet velocity, using three different fuels. It was found that the screech limit appeared to be corrollated by the relation $S_u U^{1.6}$ = constant, where $S_u$ is the laminar flame speed and U is the mixture velocity upstream of the flameholder.

Rogers (2), and Rogers and Marble (1), reported studies of screech conducted in a combustor of 1- x 4-inch cross-section, containing a 70 °/o blockage solid V-wedge flameholder parallel to the 2-inch wall. Photographic studies established that vortices were shed as described by Kaskan and Noreen. They too, observed that the vortices are shed from each lip of the flameholder with the frequency of the pressure oscillation (about 3800 cps). The mode of oscillation of screech in this combustor was identical to that observed by Kaskan and Noreen, and similarly a low-frequency (285 cps) longitudinal mode was observed.

Extensive studies of the variation of the screech limit and oscillating pressure amplitudes were made. It was found that the lean screech limit decreased strongly with increasing inlet temperatures. It was also observed that there was a discrepancy between the screech limit for increasing fuel-air ratio and that for decreasing fuel-air ratio. This was attributed to the effect of wall heating. The amplitude of the pressure oscillations was found to be insensitive to fuel-air ratio (within the screech regime) and was observed to decrease with increasing inlet Mach number. Screech became intermittent at high subsonic Mach numbers and was not attainable with choked flow at the flameholder.

Elias (7) studied the effect on screech of varying the number of V-gutter flameholders in a $2\frac{1}{2}$- x 10-inch cross-section rectangular combustor, maintaining constant blockage. He found that the mode of oscillation of screech for one, two, or three flameholders was the first, second, or third transverse mode, respectively. In each case the mode observed was such as to place pressure loops near the flame-fronts. Gas motions associated with each of these modes are shown in cross-section in Sketch C. Elias also found that the discrepancy




Sketch C: Transverse Modes of Oscillation.

between screech limits entering and leaving the screech regime was increased by a reduction of the turbulence level at the combustor inlet.

A rational approach to control or suppression of a combustion instability must be based on an understanding of its mechanism, the means by which it is sustained. Several mechanisms of screeching combustion have been proposed, however none has yet been established as correct. The most prominent of these mechanisms are discussed in the following pages in the light of the experimental evidence.

Blackshear, Rayle, and Tower (6) proposed a mechanism of screeching combustion in which the combustion process drives the oscillation by means of the fluctuations of mass combustion rate resulting from the effect of fluctuating pressure and temperature on the chemical kinetics of the system. Moore and Maslen (3) had previously utilized this concept in a theoretical study of the amplification of transverse oscillations in a cylindrical combustion chamber. They did not, however, formally propose it as a mechanism of screech. This mechanism recognizes the possibility of existence of a time lag between a pressure fluctuation and the resulting fluctuation in heat release.

Rogers and Marble (1) questioned this mechanism on the grounds that the effects of fluctuations in pressure and fluctuations in temperature due to adiabatic compression are probably small in comparison with the effect of temperature fluctuations resulting from violent mixing in the vortices.

Furthermore, there are difficulties in reconciling this mechanism with the experimental evidence. Driving by this mechanism must occur wherever combustion exists in a region of fluctuating pressure; therefore this type of driving is an essentially non-localized phenomenon. Truman and Newton's observation that fuel injection at the flameholder lip inhibits screech suggests, however, that driving must be localized, since the material immediately adjacent to the flameholder must enter the wake within a distance comparable to the flameholder width.

Consider also the effect of blockage. According to this mechanism, a combustor containing a narrow annular V-gutter flameholder situated near the combustor wall (a pressure loop for radial modes of oscillation) should exhibit pronounced screech tendencies, even though the blockage be vanishingly small. Experimentally, however, it is found that combustors of low blockage are not prone to screech.

The vortices generated during screech are the focal point of a mechanism proposed by Kaskan and Noreen (4). They are assumed to be formed by the interaction between the oscillating component of velocity and the steady flow over the flameholder lip. Their action is to extend the flame front, providing a greater burning surface. The fluctuating heat release resulting from this periodic variation of flame area is proposed as the source of excitation of screech. No provision is made for a possible time lag; burning rate being assumed proportional to flame area. This is a weakness of this mechanism since, as pointed out by Kaskan and Noreen themselves in the Author's Closure to the discussion of their paper, the time required for a small volume element of gas to traverse the thickness of a typical laminar flame is of the same order of magnitude as the period of oscillation in their combustor. Rogers and Marble (1) have also called attention to the fact that the flame front itself is a rather vague concept in a region of intense shear and turbulence, such as exists in a vortex.

Driving by this mechanism is essentially localized, since the greatest flame extension occurs at the time of vortex formation. This places the source of excitation near the flameholder. Hence, driving by this mechanism would very likely be affected by local fuel injection in the manner observed by Truman and Newton. Moreover, the requirement of high blockage may be interpreted within this mechanism as a requirement that large fluctuating pressures exist near the flameholder, where driving takes place.

Rogers and Marble (1) were first in emphasizing the important role a time lag may play in controlling screech excitation. They proposed that the screech limit, and in fact the existence or non-existence of screech in general, is determined by a time lag between the establishment of conditions conducive to burning and the resulting combustion. If this time lag were an appropriate fraction of the period of a natural acoustic mode of oscillation of the gases in the chamber, the combustion process would take place in proper phase to amplify the oscillation. Since the time lag in question is associated with ignition of a combustible mixture, it must be strongly dependent upon fuel-air ratio, gas temperature, and fuel type. Thus the existence or non-existence of oscillations in a particular chamber also depends strongly on these variables. This result agrees with the experimental observations of the screech limit.

Rogers and Marble suggested a detailed mechanism employing the time lag concept described above. In this mechanism a vortex is pictured as consisting of unburned gas, which is transported into the hot recirculation zone by the oscillating component of velocity. After the appropriate time delay this material burns, emitting a pressure wave which reinforces the pre-existing oscillation. The vortices are, in turn, generated at the lips of the flameholder by the oscillating component of velocity. Thus we have a circular sequence of events, so that, for appropriate values of the time lag, the oscillation is self-perpetuating.

As with the flame extension mechanism, driving by delayed vortex burning, as described above, would be severely affected by fuel injection near the flameholder lip. Detailed explanation of the effect awaits further knowledge of the manner in which the time lag is affected by local fuel-air ratio. The requirement of high blockage is consistent with this mechanism, as with the flame extension mechanism, since driving occurs near the flameholder in both cases. It may be observed that if the time lag becomes very small compared to the period of oscillation, this mechanism becomes indistinguishable from driving by flame area fluctuations.

It is the purpose of the present investigation to examine experimentally the phenomenon of screeching combustion with particular reference to the significance of the time lag proposed by Rogers and Marble, and secondarily to examine some details of the mechanism they suggested. It should be pointed out in particular that while their mechanism may be restricted to a certain class of combustion chambers, namely those utilizing bluff-body flameholders, the concept of the time lag purports to be generally operative in premixed gaseous systems. It is of primary importance, therefore, to strengthen evidence that this phenomenon actually does control the mechanism of screech excitation, and to devise means for measuring this quantity in advance of combustor development.

# 2. EXPERIMENTAL EQUIPMENT

The gross features of the experimental apparatus are shown in figure 1. It was designed to allow the study of screech in a low-turbulence, constant-temperature stream of a homogeneous combustible mixture. To facilitate interpretation of flame photographs the combustion chamber was made rectangular in cross-section, and a solid V-wedge flameholder was used. The resulting flow through the combustor was essentially two-dimensional. Extensive water cooling allowed extended periods of screeching operation of the combustor.

The study of screech reported in (2) was conducted in this apparatus, which, in its earlier configuration, was designed by Rogers and fabricated at his direction. Most changes made by the present author were minor developmental changes. The combustion chamber was, however, extensively modified.

## 2.1 Combustible Mixture Supply System

The main air supply originated in a two-stage rotary-vane compressor of 3200 cfm (4 lb/sec) capacity, operating intermittently to maintain a receiver at 85 to 100 psig. The air was subsequently regulated to about 85 psig and filtered through felt to remove entrained moisture and oil droplets. On entering the test cell (figure 2) the air was further reduced in pressure and regulated to 62.5 psig. The air then passed through a remote-controlled metering valve, across which the pressure drop was sufficient to maintain sonic flow. The mass flow rate was thus constant, except for minor changes owing to fluctuations of the temperature of the air entering the test cell.

On leaving the sonic valve the air was divided by coupled butterfly valves into two streams, one proceeding toward the fuel injection station and the other through a conventional shell-and-tube exchanger. These flows were then recombined, and were injected with fuel enroute to the settling chamber. A bundle of pieces of 1/4-inch copper tubing inserted in the air line just upstream of the settling chamber served to discourage upstream flame propagation in the event of flashback.

On entry to the settling chamber, the flow was more or less uniformly distributed across its 12-inch diameter cross-section by a perforated baffle plate. The turbulence level was then reduced by a battery of five 200-mesh stainless steel screens. Further protection against serious damage in the event of flashback was provided by thin aluminum rupture plates mounted in the settling chamber wall.

The final stage of conditioning of the combustible mixture was its passage through a converging nozzle and transition section of 28:1 contraction ratio. At this point the mixture entered the combustion chamber.

A commercial temperature controller was used to regulate the mixture temperature. For control purposes the temperature was sensed by a gas-filled tube inserted in the system 10-3/4 feet upstream of the settling chamber. At this point relatively high velocity prevailed, thereby reducing thermal lag in the sensing element. The coupled butterfly valves were operated by an electric motor, which was in turn operated by the temperature controller. All piping between the heat exchanger and the combustion chamber was insulated to reduce heat loss and improve regulation. The total temperature in the settling chamber was observed to fluctuate not more than $\pm 5^{o}F$ after equilibrium was attained.

The hydrocarbon fuel was pressurized and injected into the heated air through a manifold of spray nozzles situated 41 pipeline feet upstream of the settling chamber. This distance proved quite adequate for proper vaporization of the fuel for mixture temperatures above $150^{o}F$. The fuel used was a commercial paint thinner chosen for its volatility, ready availability, uniformity of composition, and general similarity to gasoline in its physical and chemical properties. In fact, it will be referred to as "gasoline" throughout this paper. Further details of properties of the hydrocarbon fuel are given in Table I.

## 2.2 Combustion Chamber

The combustion chamber used in this investigation is a modification of that used by Rogers. It was designed to allow the installation of dynamic pressure transducers in the upper and lower walls, the most appropriate locations for sensing a transverse oscillation having pressure loops at these surfaces. Components of Rogers' combustor were utilized wherever possible in the modified design.

A schematic diagram of the combustion chamber is shown in figure 3. Basically it is a 24-inch duct of 1- by 4-inch rectangular cross-section, containing a 43-degree, 70 °/o blockage, solid V-wedge flameholder. A pair of 4- by 5-inch Vycor glass windows permitted visual and photographic observation of the flow field in the near wake of the flameholder. The combustor was extensively water-cooled, including the flameholder, which had an independent cooling circuit. To prevent corrosion the combustor was fabricated throughout of stainless steel.

The upper and lower walls were made in three sections. The middle section, adjacent to the windows, extended from 1 inch upstream of the rear face of the flameholder to 4 inches downstream, and was removable. It was tapped 7/16 of an inch downstream of the flameholder to receive pressure transducers or other equipment. This section of the lower wall could also be reversed, moving the tapped location to 2-9/16 inches downstream of the flameholder. Since the threaded portion of the transducers was 1 inch in diameter, it was necessary to widen the duct throughout the length of this section. The resulting duct width between windows was 1.056 - 1.085 inches. The variation results from non-uniformity of gaskets and warpage of the glass.

The upstream and downstream sections of the upper and lower walls were permanently installed, the duct width throughout their length being 1.00 inches. Water cooling of the upper and lower walls extended from 1 inch downstream of the flameholder to the combustor exit.

The side walls upstream of the windows were semi-permanently installed and were uncooled. Downstream of the windows the side walls consisted of individually-cooled, interchangeable, removeable plates, each 4 inches in length. With all side plates in place, the combustion chamber measured 24 inches from the downstream face of the flameholder to the combustor exit. Combustor length could be varied by adding or removing side plates.

Gaskets installed between the flameholder and the windows prevented three-dimensional effects resulting from leakage around the flameholder, as encountered by Rogers.

Ignition of the combustible mixture was accomplished by a 10,000-volt spark discharge between the igniter and the rear face of the flameholder. When not in use, the igniter was retracted so that it was flush with the upper wall.

The physical appearance of the combustion chamber is shown in figure 4. Figure 4B shows a pressure transducer installed in the lower wall near the left end of the window. Here also the igniter is shown in its extended position.

## 2.3 Instrumentation

All temperatures were sensed by iron-constantan thermocouples with cold junctions maintained at $32^{o}F$. Emf readings were obtained directly from a commercial self-balancing potentiometer. Standard thermocouple tables (8) were used to reduce the data so obtained.

Steady or slowly varying pressures were measured by standard methods. Mercury- or water-filled U-tube manometers were used where the pressures to be measured were sufficiently small. Calibrated

Bourdon gauges were used to measure larger pressures.

The mass flow rate of primary air was measured by means of ASME standard orifice plates (flange taps) in the high-pressure section of the air supply system (see figure 1). Discharge coefficients used were those reported in (9) and (10). Leakage of air out of the system downstream of the point of measurement was estimated to be less than one per cent of the measured mass flow.

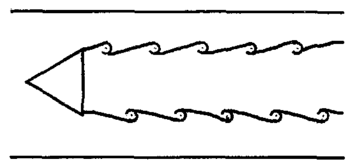
All other flow rates were measured with commercial float-type variable-area flowmeters. Flowmeters measuring the flow of gasoline were calibrated with gasoline by measuring the total weight passing through the meter in a measured time interval. Flowmeters measuring gas flow rates were calibrated with air, using calibrated orifice meters as standards.

Schlieren photographs were made with a two-mirror, single-pass schlieren system, utilizing a point light source and a straight knife edge (vertical unless otherwise specified). The light source was a twenty-kilovolt (maximum) thyratron-triggered spark, 1/5 of an inch long, oriented in the direction of light emission. Exposure times were of the order of 2 $\mu$sec. It was necessary, however, to wait several seconds between exposures to allow recharging of the spark source capacitor.

## 3. EXPERIMENTS CONCERNING VORTEX FORMATION

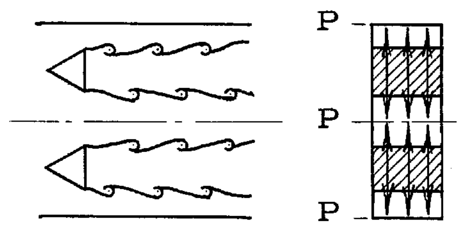
It has been observed by several investigators that screeching combustion is accompanied by the shedding of vortices from the lips of the flameholder or flameholders.

Rogers (2) observed in a two-dimensional, single-flameholder combustor the shedding of vortices from each lip of the flameholder with the frequency of the pressure oscillation. Opposite lips of the flameholder were observed to shed vortices with a relative phase difference of 180 degrees, so that the pattern of vortices appear as shown in Sketch D. Kaskan and Noreen (4) observed in a similar combustor the same pattern of vortex shedding. They too established that the frequency of vortex shedding from a given lip of the flameholder was that of the pressure oscillation.



Sketch D

Elias (7) has recently observed the shedding of vortices in a multiple-flameholder combustor. The number and size of flameholders were varied in such a way that the blockage was unchanged. The pattern of vortices shed in the single-flameholder configuration was identical to that observed in (2) and (4). As the number of flameholders was increased to two, then to three, the pattern of vortices shed from each flameholder remained identical to that observed in the single-flameholder configuration, except for a linear reduction in size. A simultaneous multiplication occurred in the frequency of oscillation, all evidence indicating an increase in mode number as the number of flameholders increased. Thus the results exhibit no essentially new features, as compared to observations in single-flameholder combustors. Each of the multiple flameholders operates as a single flameholder in a combustor of reduced size. Ames (11) had previously observed this characteristic in a multiple-flameholder combustor burning normally.




Sketch E

The vortex pattern observed with the two-flameholder configuration is shown in Sketch E. The arrows on the cross-sectional view indicate the directions of gas motion for the second transverse mode, the pressure loops of which are located on each wall and the centerline of the combustor.

Observations of vortex formation, other than the above, have not been reported. Truman and Newton (5) did, however, observe that the flamefront oscillated with the frequency of the pressure oscillation. Blackshear, Rayle, and Tower (6) observed, furthermore, that the displacement of the flamefront just downstream of flameholder lip was in phase with the pressure oscillation at that point.

To sum up the observations, it should be noted that although not every investigator reported observing the shedding of vortices during screech, neither has any investigator established an occurrence of screech, during which vortices were not shed.

In spite of the agreement between various investigators concerning the facts of vortex shedding, there is yet little agreement concerning the role the vortices play in screech excitation.

Rogers and Marble (1), consider the vortices as agents for the introduction of unburned combustible mixture into the hot wake of the flameholder. These materials are violently mixed by the turbulence in a vortex and, after a sufficient time, ignite and burn, emitting a pressure wave, which may be capable of contributing to the energy of oscillation. Kaskan and Noreen (4), on the other hand, consider the vortices to stretch the flamefront, thereby increasing the burning surface and, proportionally, the mass combustion rate. Since this process results in a periodic heat release, it too may be capable of driving the oscillation. Blackshear, et al, (6) consider the vortices to be of secondary importance, admitting, however, that they may contribute to screech excitation.

Each of the investigators who considers the vortices to be intrinsic to the screech mechanism has assumed that they are generated by the action of the oscillating velocity. This is, of course, suggested by the equality of the frequencies of pressure oscillations and vortex shedding. That such oscillations are capable of generating vortices in the observed manner has not been demonstrated. For this reason vortices generated by a sound wave imposed on the flow in a combustor operating outside the screech regime were examined.

3.1 Description of the Experiment

The study of the process of vortex generation was conducted in two parts. In the first part the combustor was operated on the lean side of the screech limit, so that smooth burning obtained. A weak shock wave was then introduced into the combustor from the upper wall so that it impinged upon the flamefront at the flameholder lip. At some time after the shock wave entered the combustor a spark schlieren photograph was taken, the instant of exposure being noted. This procedure was repeated, the photograph being taken at a later time. Using a series of such photographs it was possible to construct a simulated high-speed movie sequence showing the effects of the shock wave on the flow field. From this sequence one could determine if vortices were, in fact, generated by passage of the wave and, if so, what their characteristics were.

The second part of this experiment was a study of the vortices generated during screech. The fuel-air ratio of the mixture was increased to a value such that screech was obtained. A large number of spark schlieren photographs were then taken at random times, the phase of the pressure oscillation at the instant of exposure being noted for each photograph. These photographs were then ordered with respect to their relative phase. Thus was obtained another simulated high-speed movie sequence depicting, in this case, the formation and growth of a typical vortex during screeching combustion. This sequence was then examined and compared with the results of the first part of the experiment.

## 3.2 Equipment and Procedure

In order to carry out this experiment it was necessary to acquire a means of generating reproducible delay times between events. This was accomplished through use of a specially designed and fabricated Delayed Pulse Generator. In addition, a shock tube was required for production of the shock wave. These items are described in the following paragraphs, along with other equipment and instrumentation used in this experiment. Detailed procedures will also be described.

### 3.2.1 Delayed Pulse Generator

A specially designed Delayed Pulse Generator was used to provide a voltage pulse delayed by a known reproducible time interval from a previous pulse, which will be called the trigger signal. The trigger signal could be applied in any of three ways: (1) manually, by means of a push-button on the face of the device; (2) by shorting an internal circuit at the Internal Fire terminal; or (3) by applying a voltage pulse from an external source to the External Fire terminal.

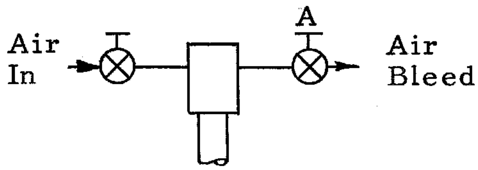
There were also three output terminals. One of these provided an immediate pulse when the trigger signal was applied. The remaining two terminals were sources of the delayed pulse.

The time delay was continuously adjustable from 50 $\mu$sec to 540 $\mu$sec by means of an external control. The range of available delay times could be altered by replacement of an internal component.

### 3.2.2 Shock Tube

The details of the shock tube used in this experiment are shown in figure 5, its physical appearance (disassembled) in figure 6. The lower section was designed for installation in the tapped hole in the upper wall of the combustor 7/16 of an inch downstream of the flame-holder. The screen over the end of the lower section served to suppress acoustic oscillations excited by the flow over the end of the tube.

Air connections to the upper section of the tube were made as shown in Sketch F. After loading the tube both valves were opened and adjusted so that the pressure in the tube was about 14 psig. The




Sketch F

tube could then be fired by closing the air bleed valve (A). On closing this valve the pressure in the upper section increased rapidly. When the pressure reached 16-18 psig, the diaphragm burst, initiating the shock wave.

Passage of the shock wave past a point in the lower section of the tube was detected by a hot-wire probe, the signal from which was highly amplified and applied as a trigger signal to the External Fire terminal of the Delayed Pulse Generator. The delayed pulse was then used to fire the schlieren light source, exposing the film in the schlieren camera, the shutter of which was open throughout the process. A commercial Pulse Interval Meter, indicating tens of microseconds, was used to measure the time delay.

In order to evaluate the strength of the shock wave a series of schlieren photographs (horizontal knife edge) were taken as it traversed the combustor. This was done in a quiescent combustor, since the presence of through-flow rendered the weak shock obscure, presumably owing to insufficient sensitivity of the schlieren system. The photographs are shown in figure 7. The number below each photograph indicates the time the exposure was made in microseconds from an arbitrary origin (not the time of diaphragm rupture).

The shock wave appears in figure 7 as a thin white arc, convex downward, sometimes multiple because of electrical oscillation of the light source. The broad, upwardly convex arc appearing in the photograph at $t = 150\,\mu sec$, and partially in the one at $t = 100\,\mu sec$, is the contact surface which originated at the shock tube diaphragm.

Measurement of successive positions of the shock wave in these photographs yielded the following information: shock propagation velocity (into room temperature air), 1320 ft/sec; shock Mach number, 1.18; static pressure ratio across shock, 1.48; contact surface propagation velocity (calculated from shock velocity), 310 ft/sec; contact surface propagation velocity (measured from photographs), 330 ft/sec.

### 3.2.3 Pressure Oscillation Phase Measurements

For the study of vortices generated during screeching combustion it was necessary to establish the phase of the pressure oscillation at which a photograph was taken. This was accomplished as follows.

The oscillating pressure was sensed by a commercial flush-mounted, water-cooled, capacitance-type transducer rated at a maximum peak-to-peak pressure of 50 psi. The resonant frequency of the diaphragm was 13, 000 cps. The detected signal from this transducer was displayed on the screen of a cathode-ray oscilloscope set for single-sweep operation, and was photographed with a Land Polaroid camera.

The sequence of events involved in obtaining a simultaneous pressure record and photograph was as follows. First, the shutter of the Polaroid camera was opened. Then the schlieren camera was snapped, triggering the Delayed Pulse Generator through the Internal Fire circuit. The immediately generated pulse was then used to start the sweep of the oscilloscope beam. At the appropriate time the delayed pulses fired the schlieren light source and marked the pressure trace. Closing of the Polaroid camera shutter ended the process. A typical pressure record obtained in this manner is shown in figure 8.

3.2.4 Measurement of Vortex Parameters

For purposes of this experiment it was necessary to take measurements from schlieren photographs of vortices. The measurements taken were x, the axial position of the vortex "centers" referred to the rear face of the flameholder, and D, the mean vortex diameter. Owing to the irregularity and partial indeterminacy of the vortex boundaries, these measurements were necessarily somewhat subjective. A certain degree of objectivity was attained, however, through the use of a commercial template, containing circular holes of various (known) diameters. By trial and error a hole could be found of such a size that as much of the vortex boundary was inside the hole as was outside it. The diameter of this hole was then identified as the mean vortex diameter. Similarly, the center of the hole was identified as the "center" of the vortex.

## 3.3 Results and Discussion

The effect of a shock wave on the flow field of a smoothly burning combustor is shown in figure 9. Indicated times of exposure t for each photograph are measured in microseconds from an arbitrary origin, chosen to approximate the time at which the shock wave entered the combustor. The direction of flow in each photograph is from left to right.

That vortices may be formed by an imposed sound wave of this type is well demonstrated by these photographs. In fact, before the disturbance disappears, a total of three clearly identifiable vortices are generated.

The apparent sequence of events occurring after entry of the shock wave into the combustor was as follows: (1) At $t = 0\,\mu$sec the shock wave is presumably just entering the combustor. The flame fronts are undisturbed and appear as a pair of thin turbulent shear layers near the upper and lower walls; (2) Just previous to $t = 0\,\mu$sec the shock wave impinged on the upper flame front near the flameholder, initiating formation of the first vortex; (3) By $t = 160\,\mu$sec the shock wave has completely traversed the combustor, reflected from the lower wall, and impinged upon the lower flame front from below, thus initiating the formation of the second vortex; (4) At t = 350 $\mu$sec the shock wave, considerably weakened by partial reflection and diffraction, has again traversed the combustor, reflected from the upper wall, and impinged upon the upper flame front from above, thus initiating formation of the third vortex; (5) At t = 540 $\mu$sec the three vortices are clearly in evidence, exhibiting the staggered pattern typical of screech in a single-flameholder combustor; (6) By t = 730 $\mu$sec the vortices are dissipating rapidly, owing to dissipative forces and continuing entrainment of new material.

It was of interest to examine the rate with which the vortices were transported downstream, their rate of growth, and the frequency with which they were generated. Figure 10 shows D, the mean vortex diameter, and x, the axial position of the vortex centers, as a function of t. The position x is observed for each vortex to increase at a constant rate after an initial period of acceleration. The rate of increase of x may be considered as the translational velocity of a vortex. The slopes of these curves yield the following values for the translational velocity: first and third (upper) vortices, about 370 ft/sec; second (lower) vortex, about 300 ft/sec. The lower value is roughly half the free-stream velocity at the flameholder lip at this operating condition, as predicted classically (12) for vortices at the interface between a moving stream of fluid and a (relatively) stagnant region of fluid. The discrepancies in translational velocities for the upper and lower vortices is believed to result from the flow of air out of the shock tube.

The mean diameter D of the first vortex is seen from figure 10 to increase linearly with t at a rate of about 160 ft/sec. This rate, being an order of magnitude or more greater than the flame speed, indicates that material continues to be entrained in the vortex as it is transported downstream.

Since temperature gradients in and curvature of the windows near the flameholder obscured photographic details in that region, it was not possible to determine accurately the times at which vortices began to form. Hence, in order to evaluate the frequency with which vortices were generated, we again refer to the curves x vs. t (figure 10). Establishing a reference station at $x = 1.0$ inch, we see that the time interval between arrival at this station of the first and third (upper) vortices is 255 $\mu$sec. The second (lower) vortex arrives at about the midpoint of this time interval.

The fact that the value of the time interval between arrival of the first and third vortices is 255 $\mu$sec is highly significant, being the period of a 3920-cps oscillation. The frequency of screeching combustion in this equipment is $3850 \pm 100$ cps. Thus we see that not only are vortices generated by an imposed sound wave of this type, but also they are formed in the same pattern and with, for all practical purposes, the same frequency as observed during screech.

Proceeding to the second part of this experiment, let us refer to figure 11, which shows a schlieren photograph typical of those taken during screeching combustion. The flow is again from the left. The typically alternating pattern of vortices is clearly seen.

The simulated high-speed movie sequence depicting the formation and growth of a typical vortex during screech is shown as figure 12. Each photograph of figure 12 shows the upper portion of the combustor only, the upper wall being on the left and the flow toward the top of the figure. The white dash near the upper left of each photograph marks the location of a hypothetical pressure transducer, the signal from which is represented as a pressure-time curve. The pressure transducer was in fact located on the lower wall, but the two locations give signals quite accurately 180 degrees out of phase. This correction was applied to the curve in figure 12. The photographs are numbered with respect to the corresponding phase of the pressure oscillation, and the time at which each was taken is indicated by an arrow to the pressure-time curve.

In each photograph of figure 12 two or more vortices may be seen. Although these vortices are actually separate entities, each will be considered as a stage in the development of a single vortex. For example, photograph number 8 shows three vortices, which will be identified as first cycle, second cycle, and third cycle vortices, counting from the flameholder. The second cycle vortex will be considered the same entity as the first cycle vortex in this photograph, but at a stage of development occurring exactly one period of oscillation later. If, for instance, reference is made in the following discussion to "number 8, second cycle," attention is to be given to photograph number 8, the second vortex from the flameholder. A nascent vortex, such as the kink in the flame near the flameholder in photograph number 2, will not be distinguished in this nomenclature from a fully-formed vortex.

In photograph number 2, first cycle, the pressure is a maximum and the perturbation velocity at or near zero. In photographs number 3 to 7, first cycle, a vortex is shown in process of formation; the pressure is decreasing and the perturbation velocity is toward the right, as evidenced by deflection of the boundary between hot and cold gas. In number 8, first cycle, the vortex is fully formed and is being transported downstream. It is clear that by number 3, second cycle, all detail interior to the vortex has vanished; thus, if any significant burning takes place inside the vortex, it is completed by this time -- about one full period, or 260 $\mu$ sec, from the beginning of vortex formation. As the vortex is transported farther downstream (number 4, second cycle, to number 6, third cycle), it gradually grows larger and becomes less distinct.

It would have been instructive to examine the vortex parameters, D and x, for this part of the experiment also; however, severe scatter rendered the data worthless. This scatter was caused, for the most part, by the action of the low-frequency longitudinal oscillation, which alternately compressed and extended the flow field in the axial direction.

The vortices formed during screech (figures 11 and 12) are in many respects quite similar to those formed by interaction of a shock wave with the flow field of a smoothly burning combustor (figure 9); they are of similar individual appearance, they exhibit the same alternating pattern, they form with the same frequency, and they form when the perturbation velocity where the vortex is formed is directed toward the flameholder.

### 3.4 *Conclusions*

This experiment has shown that (a) vortices can, in fact, be generated by the interaction of an imposed sound wave with the flow field in a smoothly burning combustor, and (b) that the vortices so formed are similar in all major respects to those generated during screeching combustion.

We may conclude, therefore, that the assumption that the vortices are formed by the action of the oscillating component of velocity during screech is, indeed, a sound one. We cannot, however, on the basis of this experiment make any inferences concerning the role the vortices play in screech excitation.

## 4. EXPERIMENT CONCERNING SCREECH SUPPRESSION

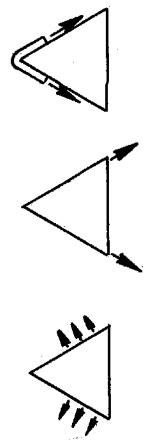
Conflicting opinions have been expressed by investigators of screech concerning the location in the combustor at which screech excitation takes place (see Chapter 1). The pressure-temperature dependence mechanism proposed by Blackshear, et al (6), would have excitation occurring at all points in the combustor at which burning takes place and the oscillating pressure is non-zero. This was the assumption made by Moore and Maslen (3) in their analysis of transverse mode amplification. Blackshear suggests, however, and in spite of the assumed mechanism, that screech excitation occurs in a small region located a short distance downstream of the flameholder. The flame extension mechanism of Kaskan and Noreen (4) and the delayed vortex burning mechanism of Rogers and Marble (1) require that excitation take place along the shear layer within a short distance of the flameholder.

At least two experimental results favor excitation near the flameholder. First, Truman and Newton (5) observed that screech occurs most readily in combustors of high flameholder blockage. The characteristics of the flow field downstream of a high-blockage flameholder array that would strongly affect a transverse mode of oscillation are: (a) The combustor contains regions of hot wake gas large compared to the regions of cold gas, so that the effective speed of sound in the transverse direction is much greater than would obtain for a low-blockage system; (b) The impedance of the flameholder array to upstream acoustic radiation approaches that of a closed end, so that a standing wave in the combustor will exhibit a pressure loop just downstream of the flameholder. Without detailed knowledge of the mechanism of screech excitation, it is difficult to determine in what way the transverse speed of sound affects the occurrence of oscillations. On the other hand, the effect of a pressure loop near the flameholder is quite clear, since the ability of any mechanism to drive an oscillation is enhanced by the existence of a pressure loop in the region of excitation. Thus, one effect of high blockage is to favor the occurrence of oscillations in which excitation takes place near the flameholder.

Another observation which favors excitation near the flameholder, also reported by Truman and Newton, is the fact that screech is suppressed by injection of liquid fuel at the flameholder lip. Fuel injected at this location can affect only conditions near the flameholder, since material in this region enters the wake within a length of combustor of the order of the flameholder width. It is not known whether this effect resulted from mechanical or thermodynamic causes. Now it is clear that modification of the mixture ratio in a local region of the combustion chamber may be used as a critical examination of whether the particular region in question plays a strong role in excitation of high frequency oscillation. In order to determine if the thermodynamic excitation of screech takes place near the flameholder an experiment was performed in which air was injected into this region. The air had the effect of leaning the mixture locally, while minimizing mechanical interference with the oscillation.

## 4.1 Description of the Experiment

Air was injected in the vicinity of the flameholder in one of three ways (Sketch G): (a) as a pair of two-dimensional jets issuing downstream from points near the apex of the flameholder; (b) as two-dimensional jets issuing from the base of the flameholder near the lips; and (c) by transpiration through porous slant surfaces of the flameholder.




Sketch G

The effect of air injection is most clearly manifested in the behavior of the lean screech limit, which may be defined as follows. The combustor, when ignited at a fuel-air ratio just above that corresponding to lean blowoff, burns smoothly. As the fuel-air ratio is increased, it achieves a value at which screech commences and continues. The overall operating condition at which screech commences is defined as the lean screech limit. Since, in this investigation, screech was usually initiated by increasing the fuel-air ratio, maintaining other variables constant, the fuel-air ratio at which screech commences will be used to identify the lean screech limit. The quantity used here to characterize the fuel-air ratio is the equivalence ratio $\phi$, which is simply the fuel-air ratio expressed as a fraction of its stoichiometric value.

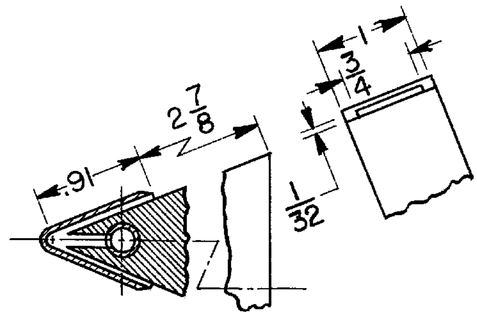
The lean screech limit will be studied in this experiment as it is affected by the amount of air injected and the manner in which it is injected. This study will be made for each of the injection methods except that of transpiration. The reason for the exception will be given in the discussion of this experiment.

Schlieren photographs were taken also. Observations made therefrom will be discussed where appropriate.

4.2 Equipment and Procedure

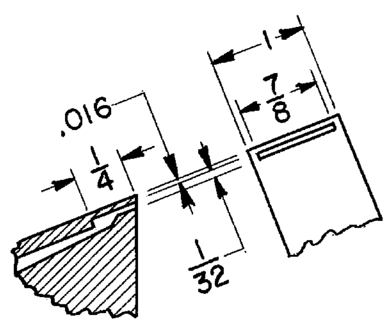
The flameholders used in this experiment are shown in figure 13. The basic dimensions of all flameholders are: height, 2.8 inches; included apex angle, $43^\circ 40'$. Water cooling was provided in all configurations, the water connections being the two projections farthest from the apex. Stainless steel was employed throughout to avoid corrosion. The projection nearest the apex is the attachment stud, which served also as the air inlet in those configurations involving air injection.

The nose injection flameholder (figure 13B) is identified by the rectangular slots, located near the flameholder apex, through which air was injected during the experiment. The air entered each side of the flameholder through the hollow attachment stud and exited parallel to the slant faces of the flameholder as shown in Sketch H.



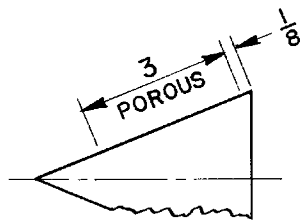

Sketch H (Not to scale)

The lip injection flameholder (figure 13C) is identified by similar rectangular slots located on the base of the flameholder near the lips. Injection air entered this flameholder in a manner similar to that for the nose injection flameholder, and similarly exited approximately parallel to the slant surfaces as shown in Sketch I (only the portion of the flameholder near the lip is shown).




Sketch I (Not to scale)

The porous wall flameholder (figure 13D) is identified by its slant surfaces, which were fabricated from commercial porous stainless steel sheet. The extent of the porous section of these surfaces is indicated in Sketch J.




Sketch J (Not to scale)

Injection air was obtained from the primary air supply upstream of the pressure regulator at entrance to the test cell. The pressure at this point was moderately affected by changes in the total demand on the air compressors. A pressure regulator was therefore provided to maintain constant injection pressure. This regulator could not properly regulate at near-maximum injection rates. This is not believed to have affected the data appreciably, however, since compressor demand changed relatively infrequently. The temperature of the injection air was not controllable, but remained practically constant at 70 $\pm$ 5$^{o}$F.

Injection rates were limited by system pressure drops to about 0.027 lb/sec with the nose injection and lip injection flameholders, and about 0.023 lb/sec with the porous wall flameholder. The parameter used here to describe the amount of air injected is $w_i/w_a$, the weight ratio of injection to primary air, expressed in per cent. Since the primary air mass flow rate was maintained at 0.3 lb/sec throughout the experiment, the limiting injection rates correspond to values of

$w_i/w_a$ of about 9 $^o/o$ and 7.7 $^o/o$, respectively.

Each observation of the screech limit was made in the following manner. With the desired flameholder installed, the primary air mass flow rate and inlet total temperature were established at the proper values. The combustor was then ignited and adjusted for smooth burning, and the injection air flow rate set at the desired value. The fuel flow rate was then slowly increased until screech commenced. Frequent observations of flowmeters, etc., were made during the increase of fuel flow. The readings last taken before commencement of screech were identified as defining the screech limit.

### 4.3 Results and Discussion

For $w_i/w_a$ less than about 3 $^o/o$, the screech limit was well defined and unambiguous for all flameholder configurations. As $w_i/w_a$ increased, however, the screech limit became less distinct; the combustor would go in and out of screech, at first irregularly, then at a more or less regular rate. Under these conditions the screech limit was established at the operating condition at which the combustor screeched about fifty per cent of the time. For very large injection rates (6 - 9 $^o/o$) continuous screech was not obtained for free stream equivalent ratios less than about 1.15; the combustor screeching about ninety per cent of the time under this condition. Higher equivalence ratios were not investigated because of the appearance of large scale aperiodic roughness of burning which frequently caused flame blowoff. Screech limit data obtained under these conditions could not be reliable.

#### 4.3.1 Air Injection Near Apex of Flameholder

Using the nose injection flameholder (figure 13B) schlieren photographs were taken showing the effect on a smooth flame of air injected at this location (figure 14). Figure 14A was taken with no air injection. Figure 14B shows the effect of 8 °/o injection. Although the air jets are not themselves visible, their apparent effect on the shear layers is to render them more turbulent and somewhat discontinuous.

Figure 15 shows similar photographs taken during screeching combustion. The vortices in figure 15A (no injection) are very regular and well defined; those in figure 15B (8 °/o injection) are well defined only very near the flameholder, becoming quite turbulent and irregularly shaped as they are transported downstream. It should be remarked that the discrepancy in axial spacing is primarily a result of the presence of the longitudinal mode of oscillation.

The effect on the screech limit of air injection at this location is shown in figure 16. The co-ordinates are $\phi_s$, the equivalence ratio at the lean screech limit, and $w_i/w_a$, the air injection rate parameter. Each curve is characterized by constant $T_t$, the inlet total temperature of the free-stream flow. All data were taken at a primary air mass flow rate $w_a$ of 0.3 lb/sec. For $T_t = 660^{\circ}R$, the corresponding value of $M_L$, the average Mach number* at the flameholder lip, was 0.5.

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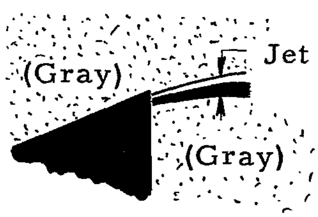
* This Mach number is that calculated for one-dimensional isentropic flow; the stagnation pressure and temperature, total mass flow rate, free-stream gas properties, and cross-sectional area at flameholder lip being known.

For all inlet temperatures, the screech limit is seen to increase continuously as air injection rate increases over the attainable range. The increase in $\phi_s$ for 9 °/o injection is seen to be 22 - 25 °/o of its value for no injection.

4.3.2 Air Injection Near Lip of Flameholder

Figures 17, 18, and 19 show schlieren photographs taken while using the lip injection flameholder (figure 13C). These photographs were taken with the schlieren knife edge horizontal in order that details of the flow near the flameholder lip might appear more clearly.

The photographs of figure 17 were taken before ignition of the combustor - - figure 17A with no injection, and figure 17B with 8 °/o injection. The jets issuing from the base of the flameholder are clearly seen in figure 17B. The knife edge is oriented so that white areas are regions where the gas density gradient is directed toward the bottom of the photograph; conversely, black areas are regions where the gas density gradient is directed toward the top of the page. The free stream air is less dense than the injection air by virtue of a 150°F temperature difference. Thus, the jet issuing near the top of the flameholder appears as in Sketch K. The spreading rate of the jet is such that it increases in apparent width by 0.182 inches in the first inch of forward motion.



Sketch K

Figure 18 shows photographs taken during smooth combustion. Comparison of the two photographs is hampered by differing sensitivity settings (knife edge penetration) of the schlieren system. It is apparent, however, that the edge of the hot wake region is at the inside edge of the jet with injection (figure 18B), rather than at the lip of the flameholder as observed with no injection (figure 18A).

Photographs taken during screech are shown in figure 19. With no injection (figure 19A) the vortices are observed to be extremely regular and well defined. The improvement in regularity over the vortices obtained with the nose injection flameholder (figure 15A) is presumably due to a more regularly developed boundary layer. The step in the profile of the nose injection flameholder trips the boundary layer at an early stage in its development.

Extreme irregularity and poor definition of the vortices are observed with 8 $^{o}/o$ injection at the lip (figure 19B). It would appear that, if vortex formation is intrinsic to the screech mechanism, then injection of air in this manner affects screech not only by modification of local mixture ratio, but also by mechanical interference with the mechanism of vortex formation.

The screech limit is affected by air injection at the lip as shown in figure 20. Again, the co-ordinates are $\phi_s$ and $w_i/w_a$, with constant $T_t$ characterizing each curve, all data being taken with $w_a = 0.3$ lb/sec as during the nose injection study.

Screech limits with no injection are seen to be somewhat higher than those obtained with the nose injection flameholder, again caused, presumably, by the altered characteristics of the flameholder boundary layer. The screech limit is observed to increase for increasing $w_i/w_a$, as obtained with nose injection. However, for $w_i/w_a$ greater than about 6 $^o/o$ ($T_t$ = 660$^o$R) the screech limit decreases in this case. The maximum increase in $\phi_s$ is 18 - 22 $^o/o$ for lip injection, as compared to 22 - 25 $^o/o$ for nose injection. The rate of increase of $\phi_s$ for small values of $w_i/w_a$ is smaller than for nose injection.

### 4.3.3 Air Injection by Transpiration

Using the porous wall flameholder (figure 13D) flame blowoff and severe flashback were encountered at injection rates as low as 5 $^o/o$. For this reason extensive screech limit measurements were not made. The following measurements were made, however: $\phi_s$ with no injection, 0.879; $\phi_s$ with 2.64 $^o/o$ injection, 0.953. Comparison with similar data obtained with the nose injection (figure 16) and the lip injection (figure 20) flameholders shows that injection by transpiration affects the screech limit to a degree similar to that obtained by the other injection methods.

## 4.4 Concluding Remarks

This experiment has shown that the screech limit is indeed affected by local modification of the mixture ratio and flowfield in the near vicinity of the flameholder lip, when these modifications are accomplished by injection of air into this region.

Air injection, as accomplished here can have no significant effect on phenomena occurring in the free-stream flow at a distance from the flameholder. Thus, since these modifications affect screech,

screech excitation must occur at some other location in the combustor. Similarly, these modifications cannot affect combustion far downstream of the flameholder, since the material injected must traverse the flame front and enter the wake within a distance of the order of a few flameholder widths.

It follows then that screech excitation must be localized in the near wake of the flameholder in a region which includes the shear layers and flamefront and which extends a few flameholder widths or less downstream.

From the above, one cannot make a conclusive argument for any of the proposed mechanisms of screeching combustion. The pressure-temperature dependence mechanism is, however, least favored of the three, since it allows excitation to take place throughout the length of the combustor.

The fact that screech excitation is a localized phenomenon has several practical implications. Since screech is considered undesirable in most combustor applications, a means of preventing it is required. The localization indicates that whatever preventative measures are applied to screech suppression, they will be most effective if applied in the vicinity of the flameholder or its near wake. Some possible preventive measures, suggested by Rogers and Marble (1), are acoustic absorption at the combustor wall, scattering of sound waves near the flameholder, and flameholder dispersion.

A possibility, so far considered only in (6), is that it may be desirable to suppress screech under some conditions, and to allow it under other conditions. For example, it might be desired to suppress screech at low altitudes and allow it to occur at higher altitudes in order to prevent the fall-off in combustion efficiency that accompanies high altitude operation of a combustor. The fact that enables us to consider operation of a combustor in screech is that at high altitudes the low combustor pressure would reduce both the peak oscillating pressure during screech and the high heat transfer to the walls which occurs under conditions of high combustor pressure. Thus the destructive ability of screech might be reduced to an extent compatible with continued operation in a combustor of normal mechanical strength. The means of controlling screech, so that its accompanying high combustion efficiency may be utilized, is provided by the results of this experiment. It is only required that additional equipment be installed in the combustor to allow controlled injection of air, fuel, or some other substance in the vicinity of the flameholder lip.

## 5. EXPERIMENT CONCERNING THE CHARACTERISTIC TIME

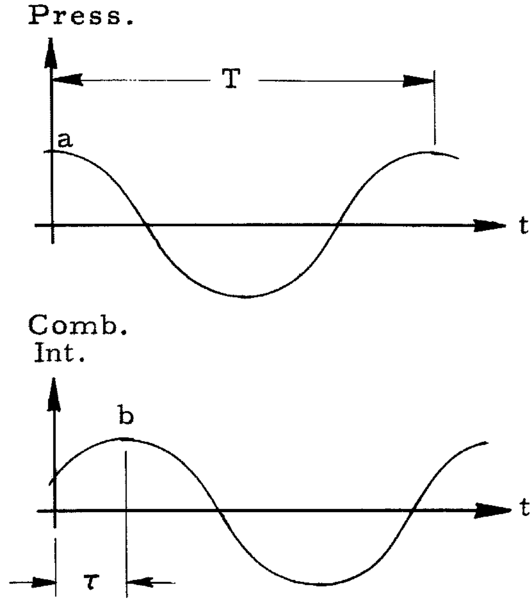
It has been suggested (1), (2) that a time lag may be the controlling factor in screech excitation. This possibility leads one to consider the question of how the existence of a time lag would be manifested in observable quantities characteristic of screech. In particular, would such a time lag affect the screech limit and, if so, in what way? Can the existence of a controlling time lag be demonstrated experimentally? These questions and more will, it is hoped, be satisfactorily answered in the following pages.

### 5.1 The Effect of a Time Lag

It has been shown that screech is a periodic instability associated with an acoustic oscillation of the gases in the combustor, and that excitation of screech occurs within the combustor just downstream of the flameholder lip. Therefore the effect of a time lag will be discussed here only as applied to periodic oscillations with internal excitation.

Let us assume that a periodic variation in combustion intensity, or mass burning rate, occurs within a region of extent small compared to the dimensions of the combustion chamber. This combustion intensity variation is to have a frequency identical to that of a co-existing acoustic oscillation. It is not necessary that the combustion intensity undergo a simple harmonic variation; however, it will be treated as if this were true, since it may always be decomposed by the methods of Fourier analysis into simple harmonic components.

Sketch L shows the simultaneous variations in combustion intensity and local pressure which might be encountered in the system described. In general, there will be a phase shift between combustion intensity and pressure. Since the independent variable is time, this phase shift may be considered as a time lag $\tau$ as indicated in Sketch L.

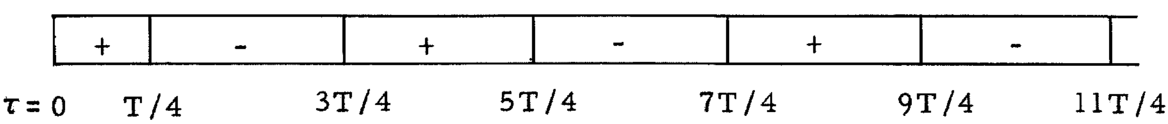



Sketch L

For vanishingly small heat additions the classical criterion for continuance of such an oscillation is that the phase shift should be less than ninety degrees. Descriptively, this means that driving will occur if peaks in combustion intensity occur at times such that the local pressure is above the mean.

Let us assume that a given peak in combustion intensity can be identified as resulting from an event that occurred at a particular time. For instance assume that the intensity peak at b in the sketch resulted from an event occurring at the time of the pressure peak at a. The time lag $\tau$ is then simply the time delay between the first event and the resulting peak in combustion intensity. We may now consider $\tau$ to be a continuously variable quantity, which may assume any positive value.

Sketch M indicates the intervals of $\tau$ which allow peaks of combustion intensity to occur at times when the local pressure is above the mean, so that driving takes place. Plus signs (+) indicate intervals allowing driving. For simple harmonic variations these intervals repeat indefinitely. It has been shown (3), however, that if the combustion process is characterized by a statistical distribution




Sketch M

of time lags, rather than a single time lag, then this picture is altered. If one then considers intervals of an average time lag, such that driving occurs, it may result that only a finite number of such intervals exist.

Assuming a time lag, or characteristic time, controls screech excitation, we must now interpret the above discussion in terms of observable quantities. Variations in the operating variables (inlet velocity, stagnation temperature, etc.) will be assumed to be manifested as changes in $\tau$ and T .

Let us suppose that the combustor is ignited at values of the operating variables such that $\tau = \frac{1}{2}T$. Referring to the previous sketch, we see then that this is a value of $\tau$ for which driving does not occur. Thus the combustor burns smoothly. If the operating variables are now slowly changed, so that $\tau$ decreases, $\tau$ may eventually attain the value T/4, at which point driving will begin and the combustor will commence to screech. The operating condition at which the ratio $\tau/T$ has, in this case, the value $\frac{1}{4}$ is then the screech limit.

If one of the operating variables (say inlet temperature) is changed from a value for which a screech limit was determined, so that the combustor again burns smoothly, and then another variable (say equivalence ratio) is changed until screech is again encountered, then another operating condition defining a screech limit is obtained. Several such observations may be made, resulting in a functional relationship between the two variables, in this case temperature and equivalence ratio. This relationship defines a set of operating conditions at which the screech limit was observed. According to the interpretation of the ratio $\tau/T$ in terms of the screech limit, it must be true that $\tau/T$ is constant at the screech limit. Therefore, a functional relationship between operating variables obtained by observing the screech limit must also be a relationship for which $\tau/T$ is invariant. Since $\tau$ is to be characteristic of the screech process, it will be referred to as the screech characteristic time $\tau_c$.

In determining whether or not a time lag controls a phenomenon the usual procedure is to measure the time lag and relate it to the occurrence of the phenomenon. This would have been very difficult to accomplish in the present case, since no means was available to measure a phase shift between oscillating pressure and combustion intensity.

An alternative procedure presents itself, however. It is possible to determine how the screech limit compares with another, measurable, time lag. If this time lag can be shown to be sufficiently similar to the assumed screech characteristic time, then significant results may yet be obtained. Such an experiment was devised, and is reported in the following pages.

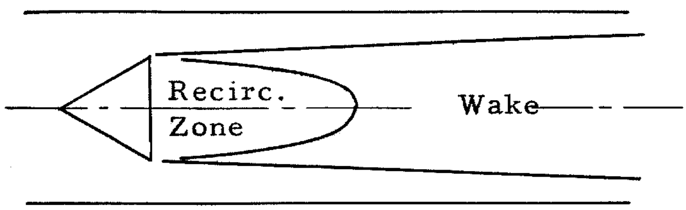
5.2 Description of the Experiment

It was demonstrated in Chapter 4 that screech excitation is a localized phenomenon, occurring in the shear layers extending downstream from the flameholder lips. Each shear layer is a thin turbulent boundary between a high-velocity, relatively cold, combustible mixture and a relatively low-velocity hot wake region consisting of products of combustion at or near the adiabatic flame temperature. Thus it is a region through which very large velocity and temperature gradients exist. Whatever the detailed nature of a screech time lag may be, it must result from phenomena occurring in this environment.

The presence of vortices may add complication to the above description of the shear layers, but in essence the situation will be similar. The shear layers may be rolled up and broken apart, but the characteristically large velocity and temperature gradients will still exist in the interior of a vortex.

In order to determine if the screech limit was characterized by constant $\tau_c/T$, it was necessary to find a measurable time lag which occurs in an environment sufficiently similar to that of a screeching combustor that its comparison with the screech limit might be meaningful. Such a time lag is that established by Zukoski (13) as the controlling variable in bluff-body flameholding.

The flow field existing in a bluff-body combustor may be idealized as shown in Sketch N. The combustible mixture separates




Sketch N

from the flameholder, flows past the shear layer bordering the recirculation zone, and eventually burns and enters the wake. The recirculation zone consists of a pair of attached eddies, the rotations of which are such that the gas velocity on the combustor centerline is directed toward the flameholder. The material in the recirculation zone is hot products of combustion. The shear layers bounding the recirculation zone are almost precisely similar to those existing in a screeching combustor. They differ only in that they are stationary, rather than oscillating, and are not disturbed by vortices.

If the centerline velocity is examined at several axial stations in the combustor, it is found that there is a point at which the velocity vanishes; at stations farther downstream, the velocity is directed away from the flameholder. The point at which the centerline velocity vanishes defines the end of the recirculation zone.

Zukoski calculated the time required for a small volume element of combustion mixture to be transported along the shear layer to the end of the recirculation zone. He found that if this time was sufficiently long, a propagating flame was established. If this time was too short, a propagating flame was not established, and the flame was said to have blown off. It was shown that this time of traverse, measured at flame blow-off, was determined solely by the chemical properties of the combustible mixture, and was independent of flameholder or combustor geometry. This time, interpreted as the time required for ignition of a small, but sufficient, quantity of combustible mixture, was termed the "ignition time delay."

Thus we see that the ignition time delay does, in fact, result from phenomena essentially similar to those which result in the screech characteristic time (if it exists). We seek then to determine what, if any, correlation exists between the ignition time delay and the lean screech limit.

The ignition time delay, as previously pointed out, is dependent only on the chemical properties of the combustible mixture. These properties are affected by the fuel type, the equivalence ratio, and the mixture temperature. Each of these quantities was varied during the following experiment.

The first part of this experiment compares the screech limit with the ignition time delay under variations in fuel type. The ignition time delay was measured for a mixture of air, gasoline, and hydrogen in various proportions. Using these measurements it was possible to obtain a relationship between equivalence ratio and fuel composition for constant ignition time delay. If a time lag similar to the ignition time delay is the controlling variable in screech excitation, then this relationship should also be satisfied at the lean screech limit. This is, of course, subject to the restriction that the period of oscillation remain constant, which was observed to be very nearly true.

The equivalence ratio at the lean screech limit was then measured, using various mixtures as used in determining the ignition time delay. This resulted in another relationship between equivalence ratio and fuel composition, which was compared with that obtained for constant ignition time delay.

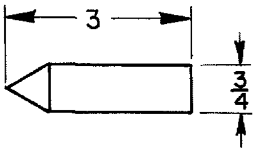
A similar experiment was performed in which the inlet temperature was the independent variable, rather than the fuel composition. Gasoline was the fuel used in this experiment.

It should be noted that in order that the relationship between operating variables defining constant $\tau$, as obtained from measurements of the ignition time delay $\tau_i$, be quantitatively identical to the same relationship, as it might be obtained by direct measurement of the screech characteristic time $\tau_c$, it is not necessary that the two times be quantitatively identical. It is only necessary that they have identical invariance properties as the variables affecting chemical properties of the mixture are changed.

## 5.3 Equipment and Procedure

Measurements of the ignition time delay were conducted in the 2- x 4-inch rectangular combustion chamber described in (14), using the cone-cylinder flameholder shown in Sketch O.

In order to determine the ignition time delay two measurements were required: (a) the length of the recirculation zone, and (b) the blowoff velocity. The recirculation zone length was measured in the following manner.




Sketch O

A fine low-velocity stream of salt solution was injected into the flameholder wake. If the point of injection was downstream of the recirculation zone, the luminosity of the hot salt did not appear near the flameholder. As the point of injection was moved upstream, however, the entire region behind the flameholder suddenly became luminous. The location of the point of injection at which this occurred was defined as the end of the recirculation zone. The length of the recirculation zone was the distance from this point to the base of the flameholder.

The blowoff velocity was obtained by increasing the inlet velocity, maintaining constant gasoline equivalence ratio and hydrogen injection rate (when used), until the flame ceased to propagate downstream. This defined the flame blowoff condition.

The ignition time delay was then obtained by dividing the length of the recirculation zone by the gas velocity just outside the wake at flame blowoff.

Screech limits were obtained in the equipment described in Chapter 2. The screech limit was approached, when using hydrogen, by increasing or decreasing the hydrogen injection rate at constant inlet velocity and gasoline injection rate. Data obtained by both methods of approach are presented in the results. When hydrogen was not being used, screech limits were obtained in the usual manner (Section 4.2).

In discussing this experiment the quantity used to characterize the relative amounts of hydrogen and gasoline is the hydrogen content parameter $\phi_H/\phi$, where $\phi_H$ is the equivalence ratio based on hydrogen only and $\phi$ is the overall equivalence ratio. For complete combustion in excess air this parameter is the weight ratio of oxygen consumed in burning hydrogen to total oxygen consumed in combustion.

## 5.4 Results and Discussion

Figure 21 shows the results of measurements of the ignition time delay for varying fuel type. The ignition time delay is plotted as a function of the overall equivalence ratio, each curve being characterized by constant $\phi_H/\phi$ . It will be noted that over the range of equivalence ratios investigated the ignition time delay increases with decreasing equivalence ratio or hydrogen content. As will be shown later, each curve would exhibit a minimum near $\phi = 1.05$. Addition of hydrogen decreases the value of the minimum ignition time delay.

The screech limits observed with hydrogen-gasoline fuel were generally well-defined. However, screech limits could not be obtained in the normal manner ($\phi_H$ increasing) if $\phi_H/\phi$ exceed about 0.3. For higher hydrogen concentrations the combustor, when not in screech, burned very roughly. At times the roughness of burning caused flame blowoff. Under such conditions the combustor would not operate in "smooth" combustion long enough to obtain reliable screech limit data. For this reason the method of obtaining screech limits was, in a sense, reversed. The combustor was ignited in screech and $\phi_H$ was decreased until screech ceased. Screech limits obtained in this manner were of the order of 4 °/o lower for low hydrogen concentrations than those obtained by increasing $\phi_H$. For the higher values of hydrogen concentration the per cent difference in screech limits decreased.

Obtaining screech limits by decreasing $\phi_H$, another obstacle to reliable screech limit measurement was encountered for $\phi_H/\phi$ greater than about 0.47. For such values a very violent low-frequency disturbance occurred before screech ceased. This disturbance aurally resembled a periodic detonation.

Results of screech limit measurements with hydrogen-gasoline fuel are shown in figure 22. The co-ordinates are $\phi_s$, the equivalence ratio at the lean screech limit, and $\phi_H/\phi$, the hydrogen content parameter. Two screech limit curves are shown: one for lip Mach number $M_L = 0.5$, and one for $M_L = 0.7$. The dash lines are lines of constant ignition time delay, cross-plotted from figure 21.

It was shown earlier that, if a characteristic time controls screech excitation, if the characteristic time has the same invariance properties as the ignition time delay, and if the period of oscillation remains constant, then a screech limit curve should coincide with a line of constant ignition time delay. Within the range of hydrogen concentrations investigated, the maximum deviation of the screech limit curve from the constant $\tau_i$ curve with which it is coincident at $\phi_H/\phi = 0$ is seen to be 9 °/o of the total change in $\phi$ at constant $\tau_i$ for $M_L = 0.5$, and 20 °/o of the total change in $\phi$ at constant $\tau_i$ for $M_L = 0.7$. These deviations occur at $\phi_H/\phi = 0.6$.

The observed deviations may be at least partially explained in the following ways. First, it was observed that as $\phi_H/\phi$ increased, the frequency of screech increased by 10 - 15 °/o, thus the period of oscillation T decreased by the same percentage. Since $\tau_c/T$ is the parameter which is to be constant at the screech limit, then $\tau_c$ must also decrease, as observed for $\tau_i$. Secondly, the vortices generated during screech must affect the characteristic time, since they affect the configuration of the shear layers. The density and lip velocity variations which take place as the hydrogen concentration increases may affect the vortices in some manner, and thus the characteristic time.

We will now consider the portion of the experiment in which the ignition time delay was varied by varying the inlet temperature (figure 23). Each of the curves of figure 23 is characterized by constant inlet total temperature $T_t$. These curves clearly exhibit the minimum time delay previously mentioned. It will be noted that $\tau_i$ increases for decreasing $\phi$ or $T_t$.

Figure 24 shows the variation of the equivalence ratio at the lean screech limit with inlet static temperature* at the flameholder

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* The static temperature was calculated from $M_L$ and $T_t$, assuming one-dimensional isentropic flow from the settling chamber.

lip. The appearance of the flame before and during screech was as normally observed, and the screech limit was well-defined.

The dash lines in figure 24 are lines of constant ignition time delay, cross-plotted from figure 23 and corrected to static temperature. Again, it is expected that a line of constant ignition time delay should coincide with the screech limit curve, and again this is very nearly true. In this case the maximum observed deviation of the screech limit curve from a line of constant ignition time delay, in per cent of the change in $\emptyset$ at constant $\tau_i$, is about 20 $^o/o$.

For this experiment no observations of screech frequency were made; however, owing to the increase in inlet temperature (thus also the adiabatic flame temperature), the screech frequency should increase and T should decrease, so that $\tau_c$ should decrease as previously explained. During this experiment the inlet velocity varied to a much greater extent than when varying the fuel type. Since this data was taken at constant Mach number, the inlet velocity varied approximately as the square root of the inlet temperature. Thus the generation of vortices was more strongly affected during this experiment than during the previous one. A further explanation of the observed deviation lies in the effect of heat transfer from the combustible mixture to the flameholder. The effect of such heat transfer is to reduce the temperature of the gas entering the shear layer near the flameholder. Thus the temperatures indicated in figure 24 actually exceed the effective inlet temperature by an amount which increases approximately as the temperature difference between the free-stream combustible mixture and the flameholder. Since the inlet temperature was calculated from $M_L$ and $T_t$, the fact that $M_L$ is only an "average" Mach number will also affect the effective inlet temperature. The actual Mach number at the flameholder lip exceeds that at the combustor wall. Thus the static temperature at the flameholder lip must be less than that calculated from $M_L$ and $T_t$, affecting the screech limit as does heat transfer.

## 5.5 Concluding Remarks

The above experiment has conclusively demonstrated that the screech limit follows closely a line of constant ignition time delay. It appears clear, then, that a characteristic time does, in fact, control screech excitation. Furthermore, the screech characteristic time must result from phenomena very similar to those resulting in the ignition time delay of bluff-body flameholding.

Some recent observations by E. E. Zukoski (14) further substantiate the above conclusions. These observations were made in a 2- x 2-inch combustor, 24 inches long. The flameholder used was a 70 °/o blockage solid V-wedge as used in the present investigation. Normal screech (sharp limit, high amplitude) was not encountered in this combustor at any operating condition while burning gasoline only. On addition of hydrogen to the mixture screech was definitely encountered at a frequency of 8000 cps, the natural frequency of oscillation of the first transverse mode in this combustor. Recall that the screech frequency in the 1 x 4 combustor was 4000 cps.

This result is interpreted as follows. The natural frequency doubled in reducing the transverse dimension by a factor of two. Similarly the period of oscillation halved, since it is inversely proportional to frequency. Hence, for $\tau_c/T$ to be constant at the screech limit, the value of $\tau_c$ at the screech limit must also have been halved.

Refer again to figures 23 and 24. Screech at 4000 cps was obtained in the 1- x 4-inch combustor at $\emptyset = 0.81$ for $T_t = 660^{\circ}R$ ($T_L = 600^{\circ}R$). The value of the ignition time delay at this operating condition is about 0.36 msec. In order to obtain 8000-cps screech in the 2- x 2-inch combustor it must be possible to reduce $\tau_i$ (considering it proportional to $\tau_c$) to one-half of 0.36 msec, or 0.18 msec. This value cannot, however, be achieved with a gasoline-air mixture at $660^{\circ}R$. Thus screech should not be encountered under these conditions.

Figure 21 shows, on the other hand, that an ignition time delay of 0.18 msec is readily attained with a gasoline-hydrogen-air mixture. If this is the case, then screech should be encountered if sufficient hydrogen is added. This is in accord with the experimental observation.

It is not unreasonable at this point to ask why screech could not be achieved in the 2- x 2-inch combustor by leaning the mixture, so that the characteristic time increased. For example, referring to Sketch M (Section 5.1), if the observed screech limit was such that $\tau_c/T = 5/4$, then why could not screech be achieved by lowering the equivalence ratio so that $\tau_c/T$ is increased to the value 7/4 ? Since a vortex becomes more diffuse as it grows and is transported downstream, the burning of the vortex is very likely spread over a considerable time interval, so that if burning of the vortex is delayed by more than one period of oscillation, then part of its energy is released at such times as to damp the oscillation rather than sustain it. Furthermore, since the energy is released far downstream of the flameholder, it is less effective in affecting conditions near the flameholder, owing to downstream radiation, viscous dissipation, the effect of the through-flow in retarding upstream radiation, etc. Each of these effects reduces the ability of vortex burning to drive the oscillation. Thus screech should not be expected to occur for large values of $\tau_c/T$ .

The ratio $\tau_c/T$ is the similarity parameter characteristic of the coupling between the acoustics of the combustor and the combustion process, and can be of great practical use in combustion chamber development. It is the parameter which enables us to predict the results of changes in combustor dimensions, fuel type, and (partially) inlet temperature. Thus observations of screech in a scale model combustor enable us to predict its existence or non-existence in the projected design.

Suppose that a combustor of characteristic dimension $\ell$ is known to screech at a particular operating condition. Knowing the operating condition and fuel type, we may determine the corresponding value of the characteristic time, as represented by the ignition time delay. Knowing also the screech frequency observed, we may calculate T, and from now known quantities we may calculate the ratio $\tau_i/T$ at which screech commenced.

Now, for similar geometry and inlet conditions, $\tau_c/T$ is constant at the screech limit for a particular mode of oscillation. Thus, since the behavior of $\tau_i$ is known and is very nearly that of $\tau_c$, and since T is (approximately) constant in a given combustor, we may predict the behavior of the screech limit for the mode of oscillation in question as the fuel type or inlet temperature is varied. The error in the predicted variation in $\phi_s$ should be less than 20 °/o of the predicted variation. Experience with the present combustor indicates that the direction of the error will be such that the predicted variation of $\phi_s$ will be greater than the actual variation.

The recent results on changing combustor size (Section 5.5) suggests also that we may predict the behavior of the screech limit for changes in the combustor characteristic dimension $\ell$, maintaining geometric similarity in addition to similarity of inlet conditions. For this type of variation, we must have T proportional to $\ell$. Then, since $\tau_i/T$ is to remain constant, the value of $\tau_i$ at the screech limit must also be proportional to $\ell$. All else being constant, we may then determine the change in $\phi_s$ corresponding to the given change in $\ell$. If it results that, in order for screech to occur in a combustor of reduced size, $\tau_i$ must decrease below the minimum value attainable, then screech will not be observed in the reduced combustor.

The error in predicting the variation of $\phi_s$ should be to some extent reduced if the procedures described are modified to account for the changes in T that occur as the operating condition is changed. To the first order of approximation T may be considered proportional to the square of the speed of sound in the hot wake gas, which, for this purpose, may be considered to consist of completely-reacted products of combustion at the adiabatic flame temperature. It should be pointed out, however, that this correction will be significant only for equivalence ratios near that corresponding to maximum adiabatic flame temperature. That this is true results from the insensitivity of the equivalence ratio to changes in time lag when the mixture is very lean (figures 21 and 23).

It is now appropriate to consider the implications this experiment can have on the mechanism of screech excitation. Certainly one fact is obvious; namely, the controlling variable in the mechanism must be a time lag, or characteristic time. Furthermore, this time lag must result, at least in part, from the same phenomena that result in the ignition time delay of bluff-body flameholding. In other words it must result from the sudden confluence of a high-speed, relatively cold, combustible mixture and a relatively stagnant gas consisting of hot products of combustion, forming a turbulent shear layer with large temperature gradients. The screech characteristic time must, however, be affected not only by the variables controlling the chemical properties of the mixture, but also by aerodynamic variables through their effect on vortex generation.

The delayed vortex burning mechanism of screech excitation fits the above specifications very closely. Thus, of the mechanisms so far proposed, it is the most highly favored by the results of this experiment. However, as pointed out in (4), one cannot over-emphasize the difficulty of establishing any mechanism as being correct in detail.

## 6. CONCLUDING REMARKS

The vortices generated during screeching combustion have been generally assumed to be formed by the action of the oscillating component of velocity. By imposing a weak shock wave on the flow field of a smoothly burning combustor it was demonstrated that this assumption is a sound one.

The fact that screech excitation occurs in the shear layers immediately downstream of the flameholders was demonstrated by injection of air into this region and observing the effect produced on the screech limit. This experiment demonstrated, furthermore, that such injection suppresses the tendency of the combustor to screech. The results of this experiment are of considerable practical importance. The combustion chamber designer is often faced with the problem of ridding an existing combustor of the tendency to screech. On the other hand, under favorable conditions it might be desirable to allow screech to occur, thereby reaping the benefits of its accompanying high combustion efficiency. From the results of this experiment it is apparent that efforts to control or suppress screech must be directed at phenomena in the near wake of the flameholder. Specificially it was demonstrated that injection of air in this region suppresses the screech tendency of a combustor. Other substances may, of course, be used. Hydrogen, because of its characteristic of decreasing the characteristic time, might be used to initiate screech, rather than to suppress it.

By comparison of the observations of the screech limit with ignition time delay data obtained from bluff-body flameholding studies it was shown that the mechanism of screech excitation is controlled by a characteristic time. Furthermore, this characteristic time is similar in its invariance properties to the ignition time delay of bluff-body flameholding. In fact, it was shown that invariance of the ratio of the ignition time delay to the period of oscillation predicts the screech limit for a given Mach number of the inlet flow. This result enables us to predict the occurrence of screech in a family of geometrically similar combustors using various fuel types. Measurements of the screech limit need be made on only one of the combustors in the family, but for each different mode of oscillation encountered. The variation of $\tau_i$ with fuel type, temperature, etc., may then be obtained from a simple flame stabilization (non-screeching) experiment.

Insofar as the mechanism of screech excitation is concerned, it has been shown that its controlling variable must, as predicted by Rogers and Marble, be a time lag resulting from physical processes similar to those resulting in the ignition time delay of bluff-body flameholding. One cannot conclude from this, however, that the delayed vortex burning mechanism proposed by them is correct in detail.

In order to illuminate the mechanism of screech excitation further and extend the usefulness of the similarity parameter $\tau_c/T$, further experimentation is indicated.

First, it is possible that a direct measurement of the screech characteristic time might be made by taking high-speed photographs exposed by the light emitted from the burning fuel. Development of a camera to accomplish this experiment was initiated during the present investigation, but was not completed owing to deficiencies in currently available electronic equipment.

Secondly, the application of the parameter $\tau_l /T$ to changes in combustor size should be placed on a sounder basis by measurements of the screech limit as the characteristic dimension of geometrically similar combustors is incrementally changed. The experiment of this type reported in Chapter 5 was done with incomplete instrumentation, and is purely qualitative.

Finally, screech control by local injection should be further investigated, using a variety of additives carefully chosen for their effect on the characteristic time. By this means a truly effective and practical means of screech control will likely be developed.

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TABLE I.

Properties of Hydrocarbon Fuel Used in this Investigation

| | | |
|---|---|---|
| Heat of combustion, net: | 18,675 BTU/lb | |
| Average molecular wt.: | 96 | |
| Latent heat of vaporization at 77°F: | 148 BTU/lb | |
| Vapor pressure at 100°F: | 2.5 p.s.i. | |
| Density, specific at 60°F: | 0.7366 | |
| Density, lb/gal at 60°F: | 6.132 lb/gal | |
| Hydrocarbon type analysis: | Saturates | 94.5 °/o |
| | Olefins | 00.5 °/o |
| | Aromatics | 5.0 °/o |

Distillation ASTM :

| | |
|---|---|
| Initial | 172°F |
| 5 | 179 |
| 10 | 180 |
| 20 | 183 |
| 30 | 186 |
| 40 | 188 |
| 50 | 191 |
| 60 | 195 |
| 70 | 198 |
| 80 | 202 |
| 90 | 208 |
| 95 | 214 |
| Dry | 224 |

Chemical Analysis (Proportions by weight):

| Carbon | Hydrogen |
|---|---|
| 85.4 °/o | 14.6 °/o |

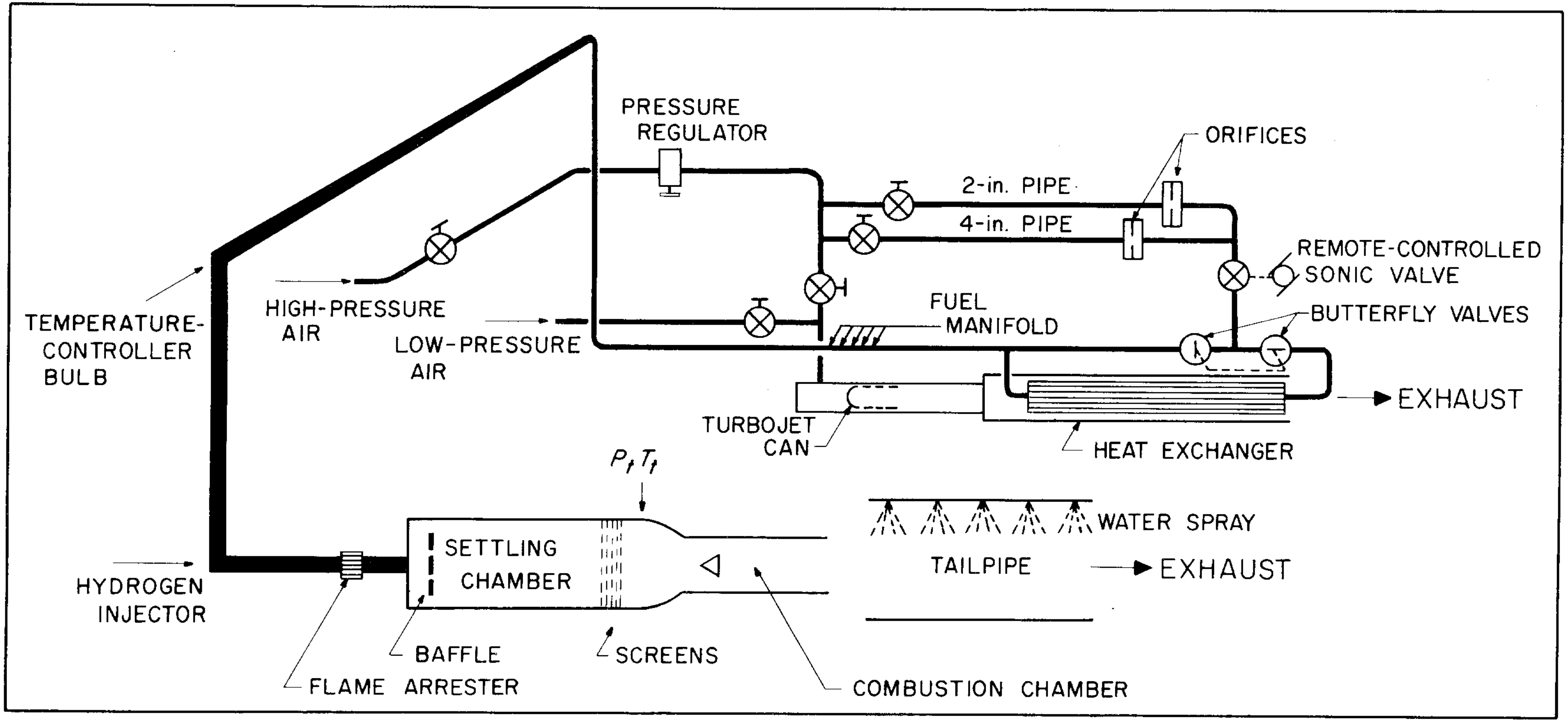



Figure 1 — Schematic diagram of experimental apparatus

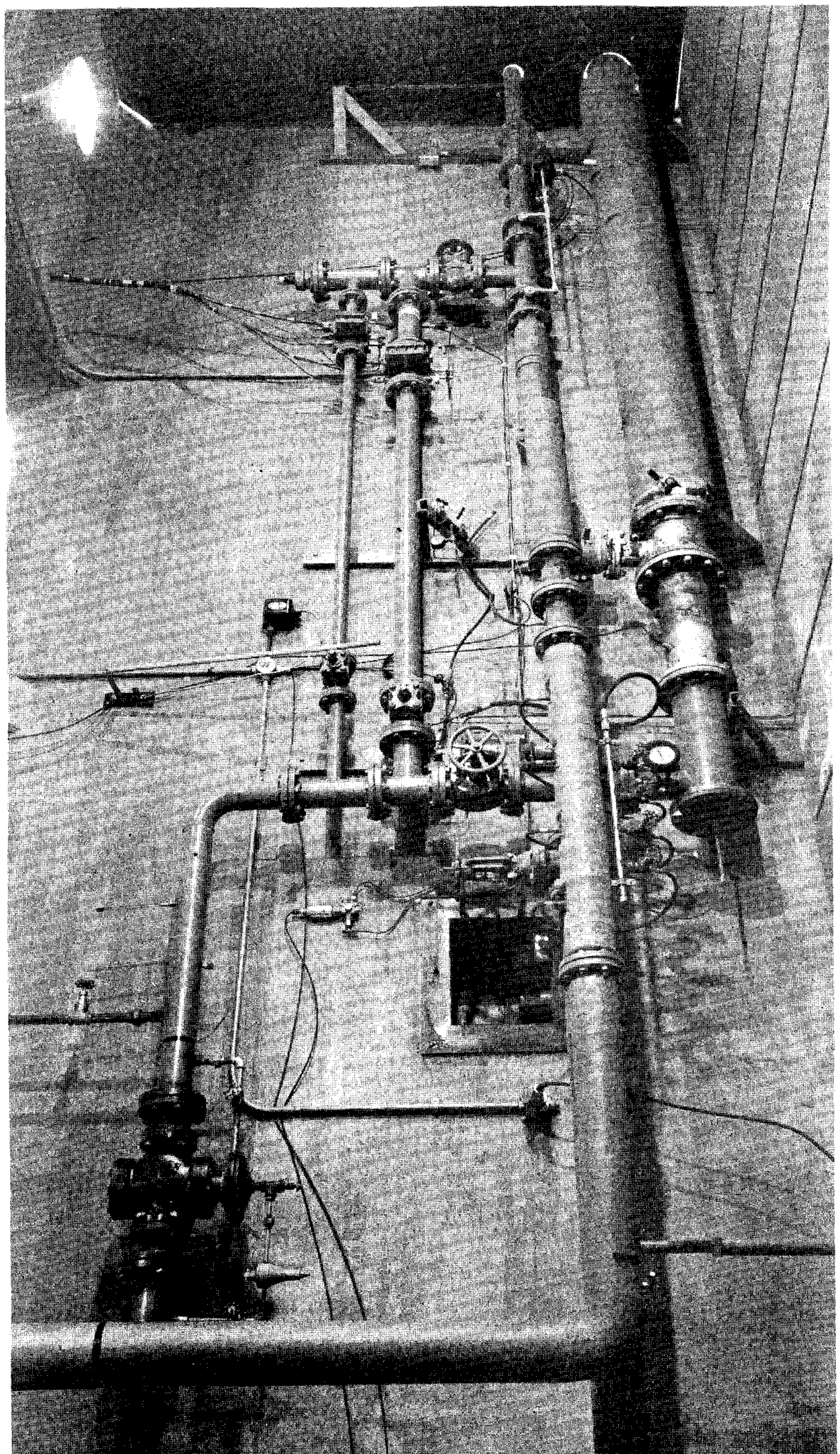


Figure 2 — Air metering and heating system

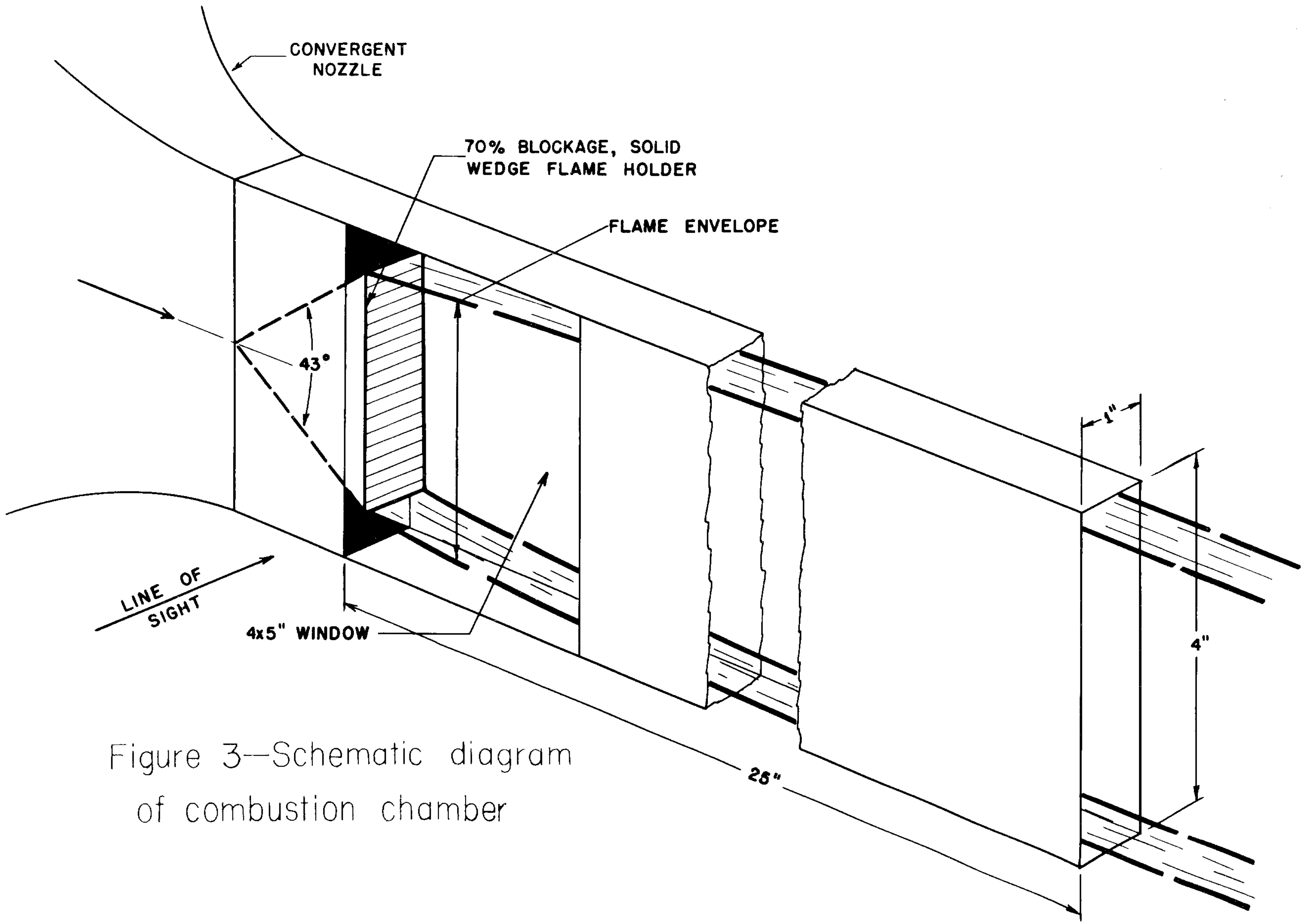



Figure 3—Schematic diagram of combustion chamber

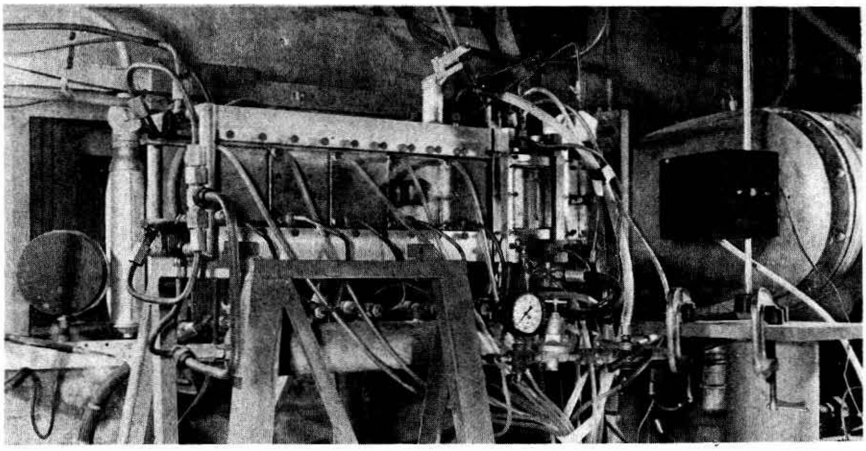


FIGURE 4A — SIDE VIEW OF COMBUSTION CHAMBER

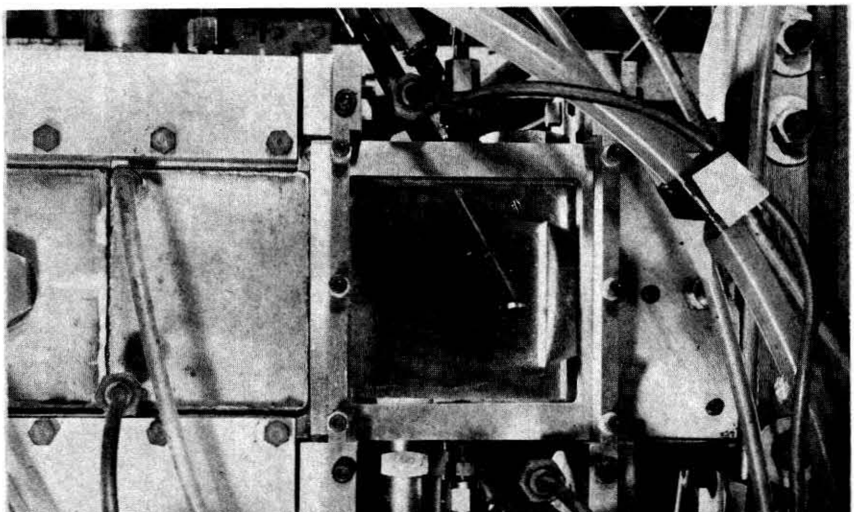


FIGURE 4B — CLOSE-UP OF WINDOW AREA

Figure 4 — Combustion chamber

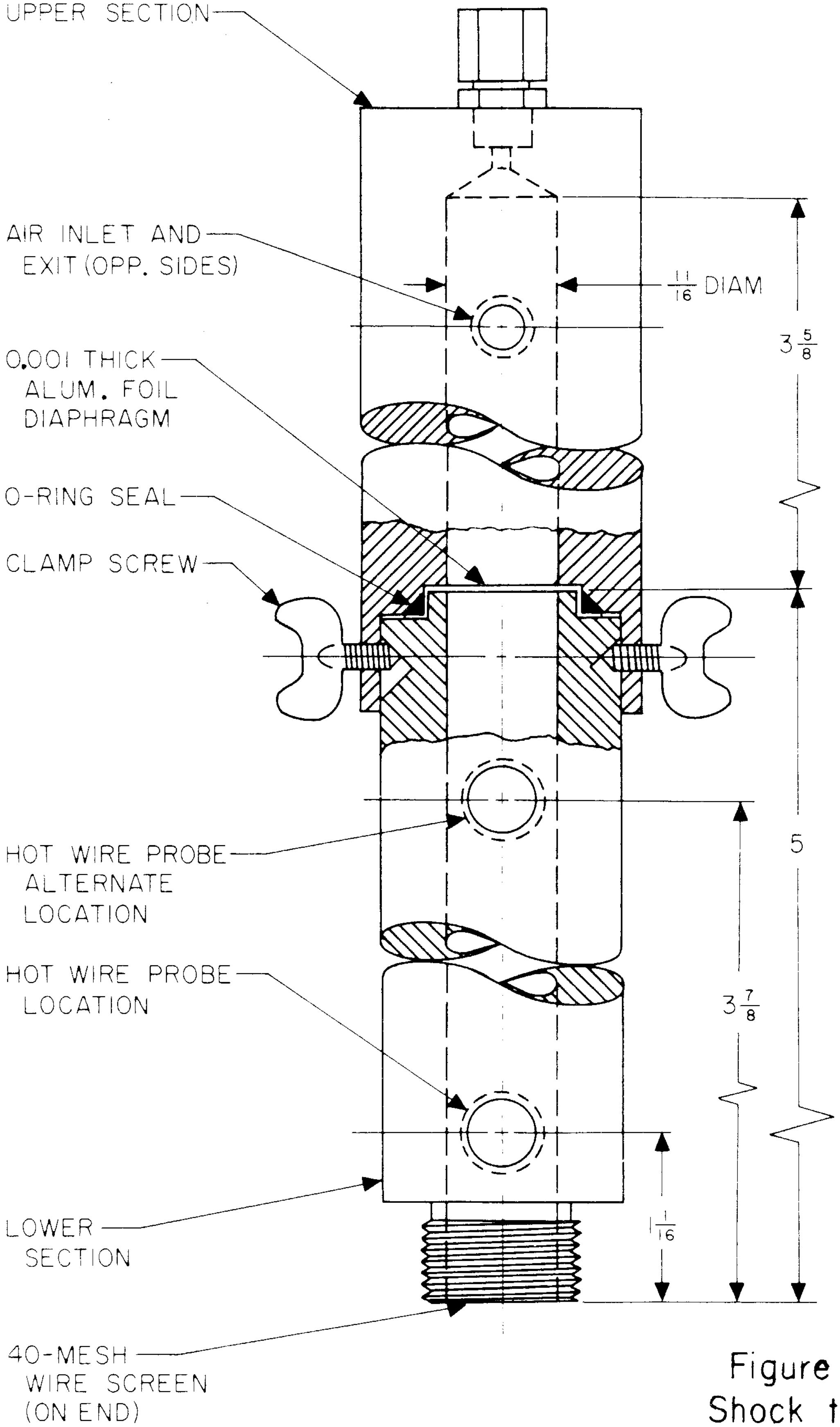



Figure 5
Shock tube

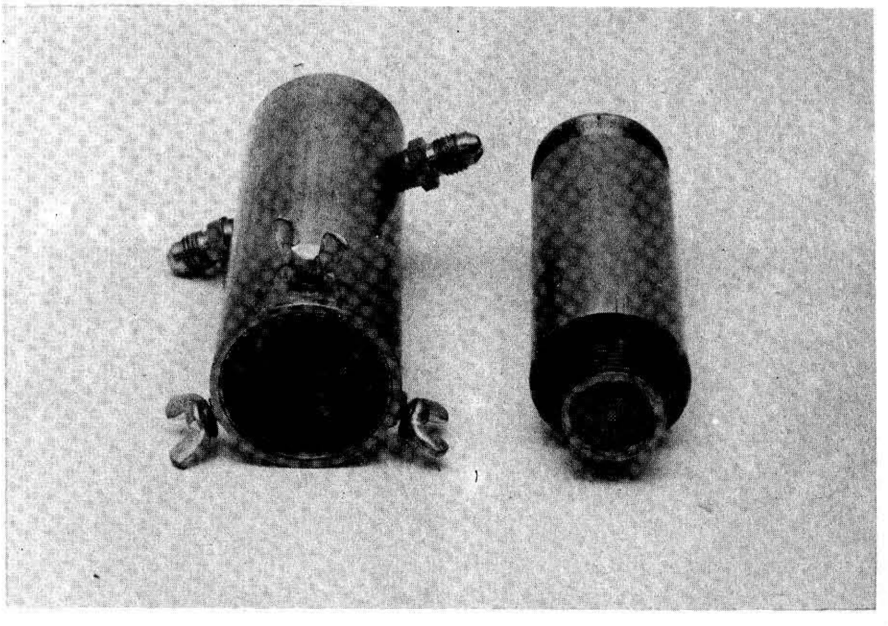
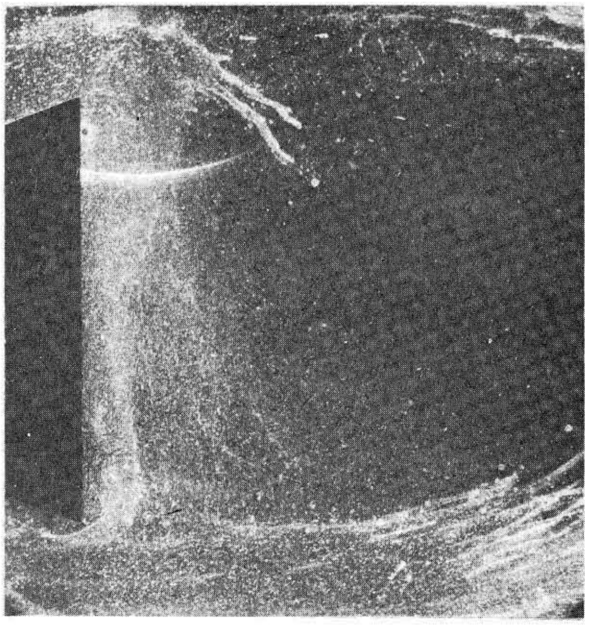
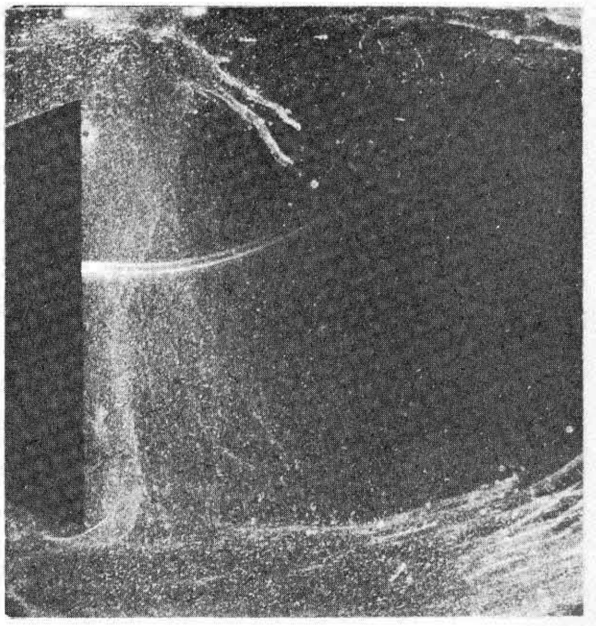


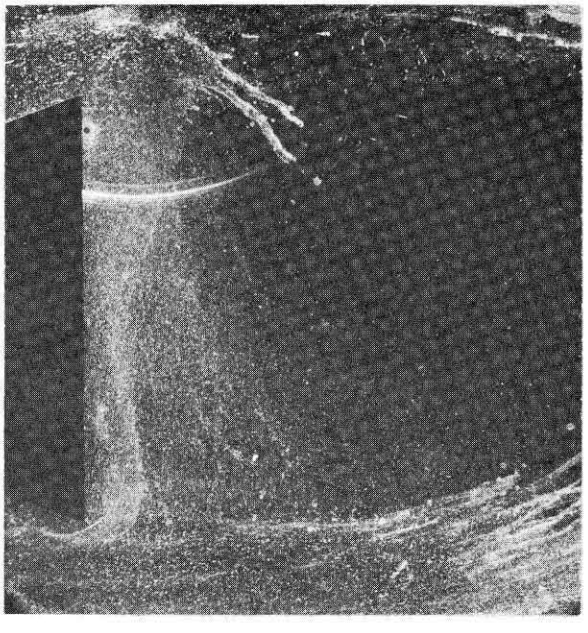
Figure 6—Shock tube



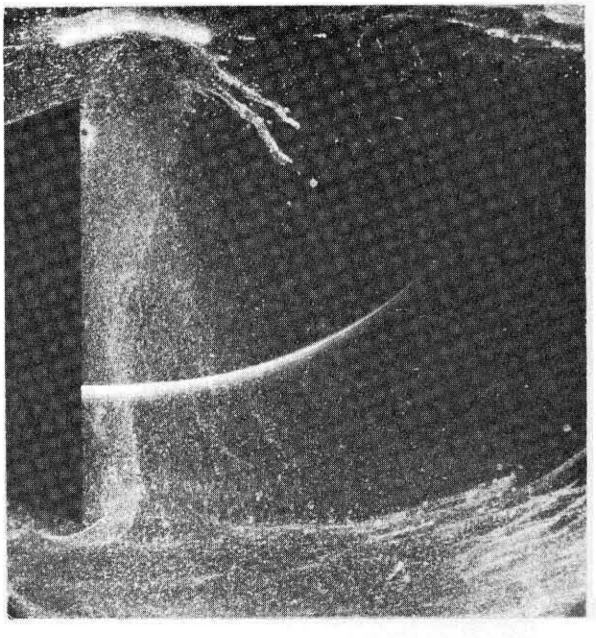
t=50



t=100



t=70



t=150

Figure 7 — Propagation of shock wave into quiescent duct (t=time in microseconds from arbitrary origin)

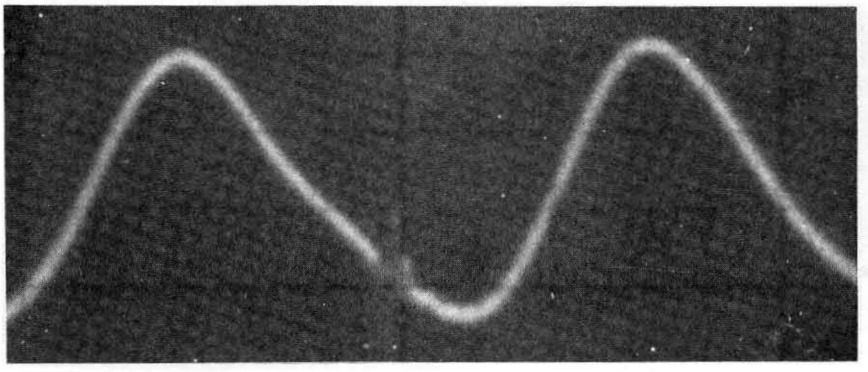


FIGURE 8 — PRESSURE WAVEFORM WITH GASOLINE FUEL: SHOWING TIMING MARKER

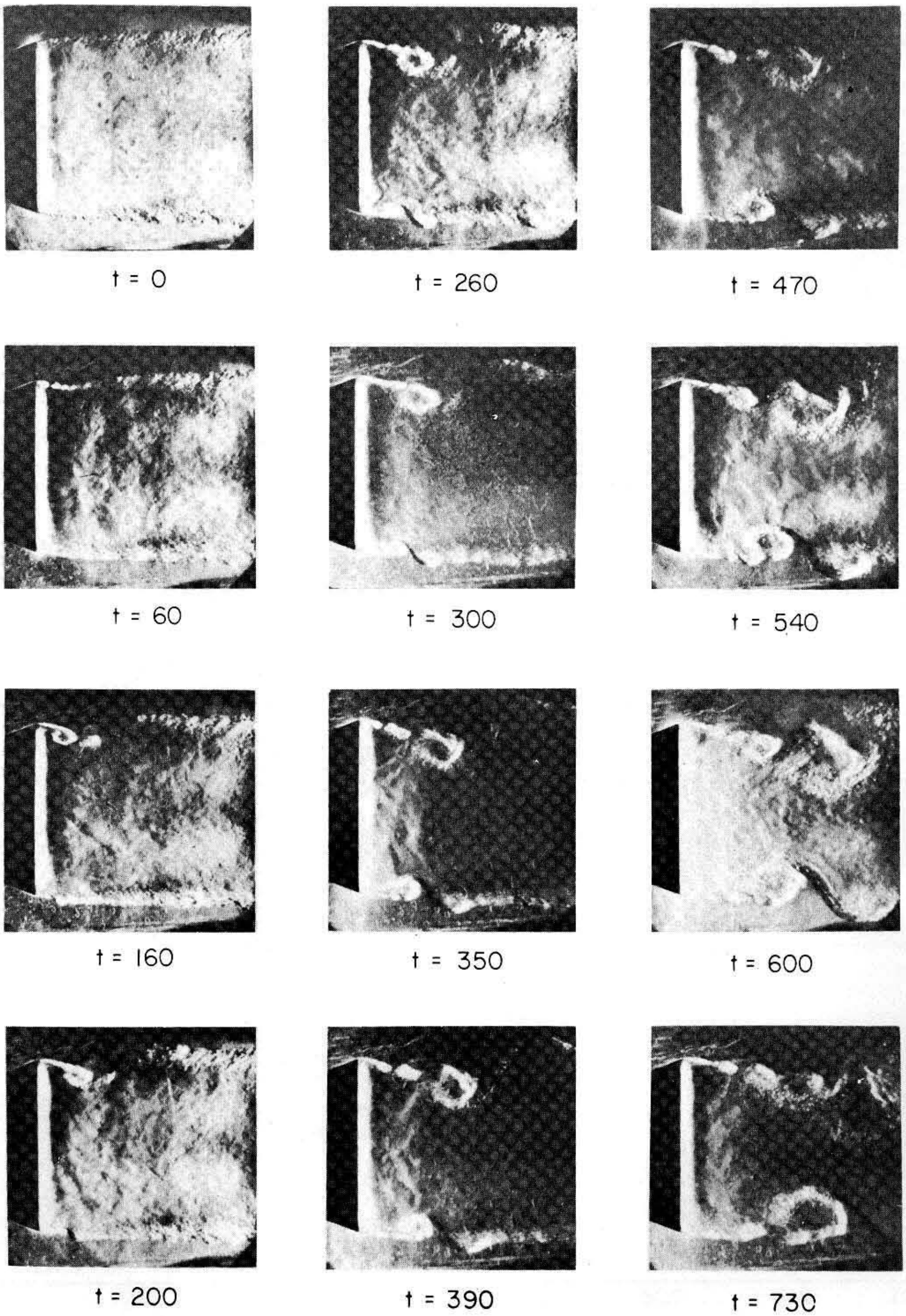



Figure 9– Development of shock-induced vortices (t = time in microseconds from arbitrary origin)

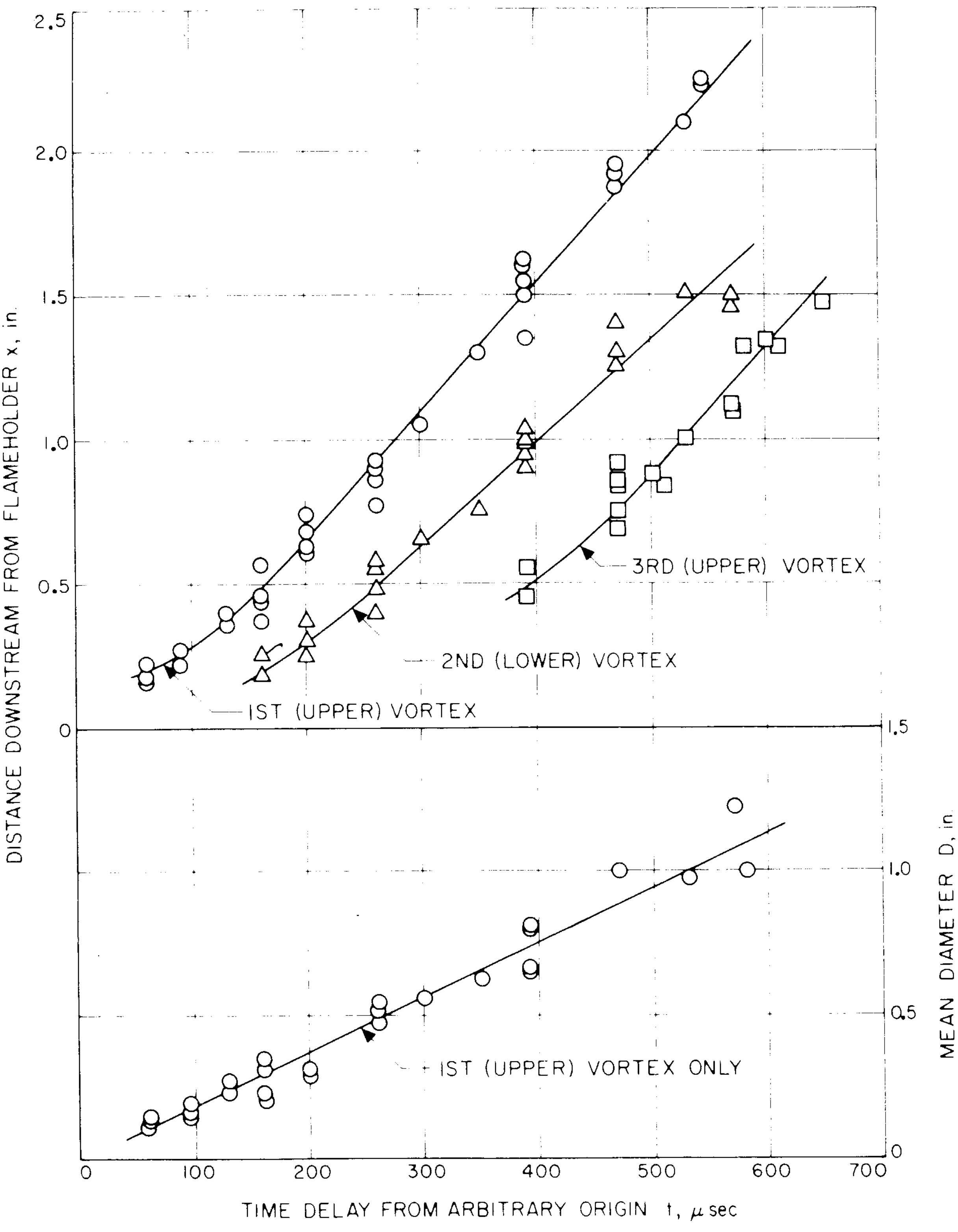



Figure 10 — Diameter and position of shock-induced vortices

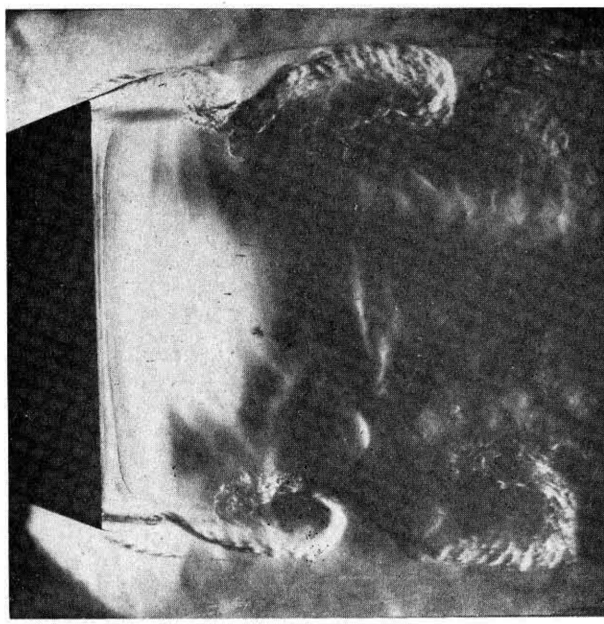


Figure 11 – Schlieren Photograph:
Screeching Combustion

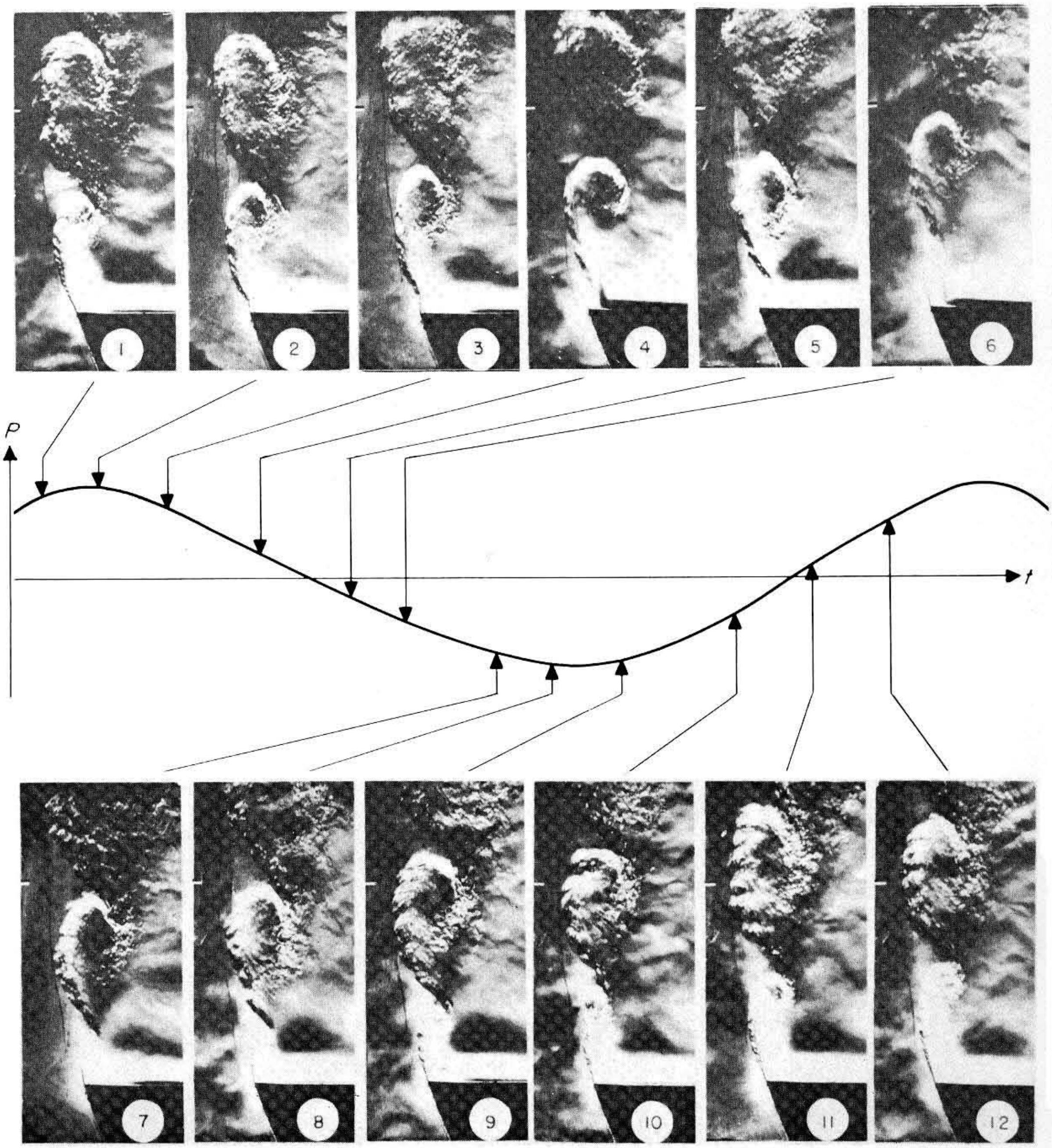



Figure 12 - Typical cycle of screeching combustion

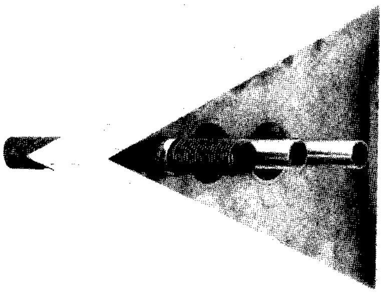


FIGURE 13A — BASIC FLAMEHOLDER

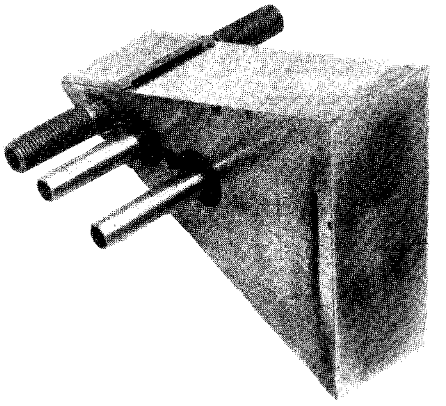


FIGURE 13B — NOSE INJECTION

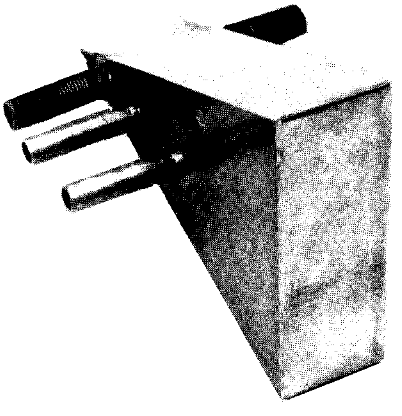


FIGURE 13C — LIP INJECTION

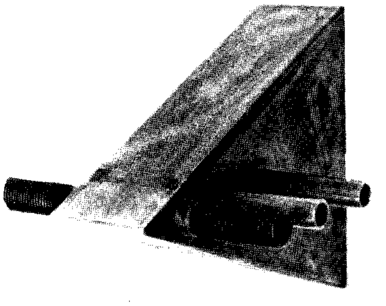


FIGURE 13D — POROUS WALL

Figure 13—Flameholder configurations

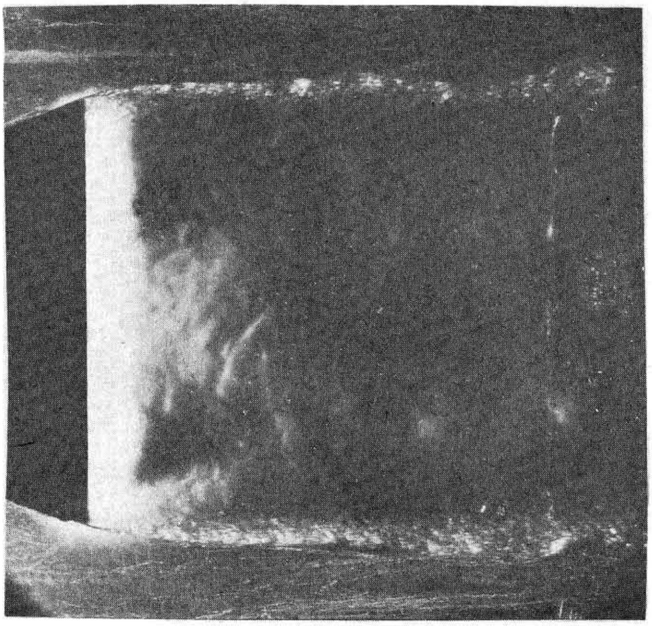


FIGURE 14A — $w_i / w_a$ = 0%

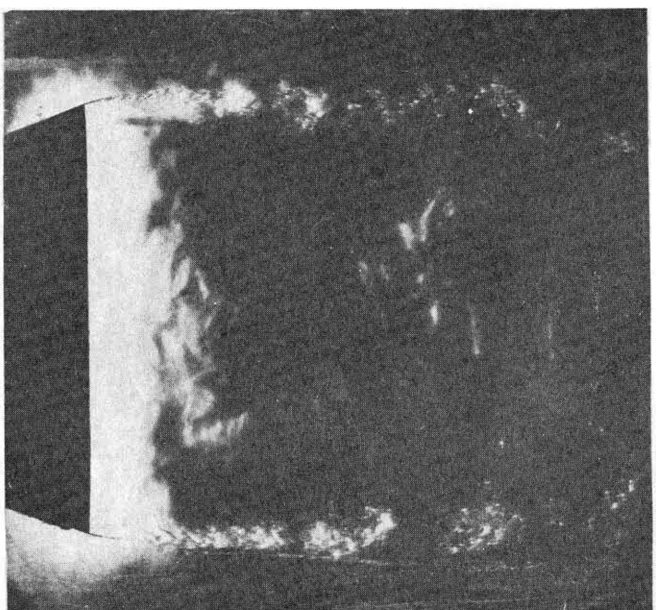


FIGURE 14B — $w_i / w_a$ = 8%

Figure 14 — Schlieren Photographs:
Smooth combustion;
Nose injection

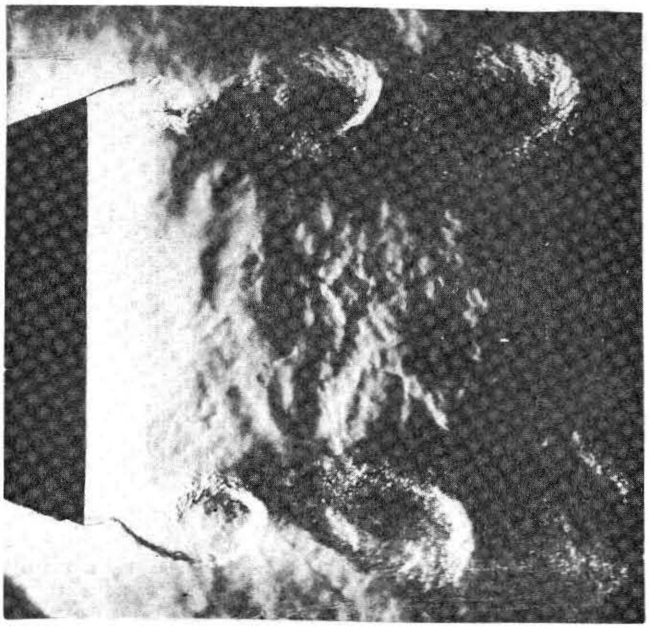


FIGURE 15A– $w_i/w_a = 0\%$

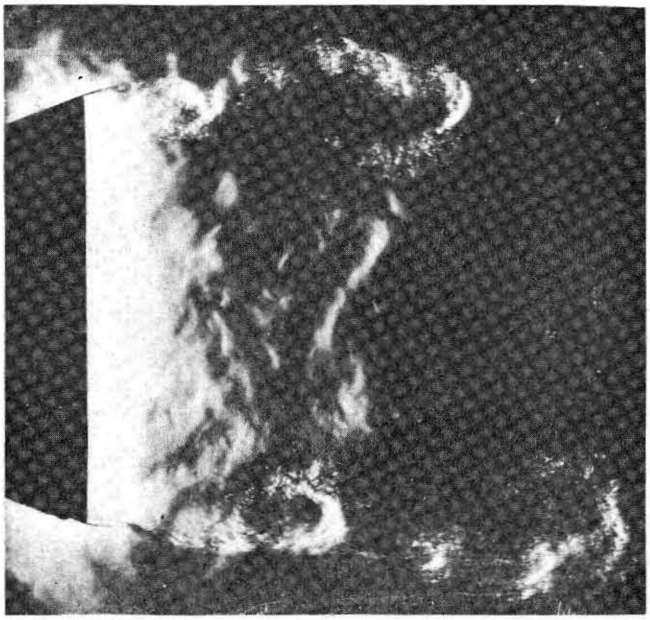


FIGURE 15B– $w_i/w_a = 8\%$

Figure 15 — Schlieren Photographs: Screeching combustion; Nose injection

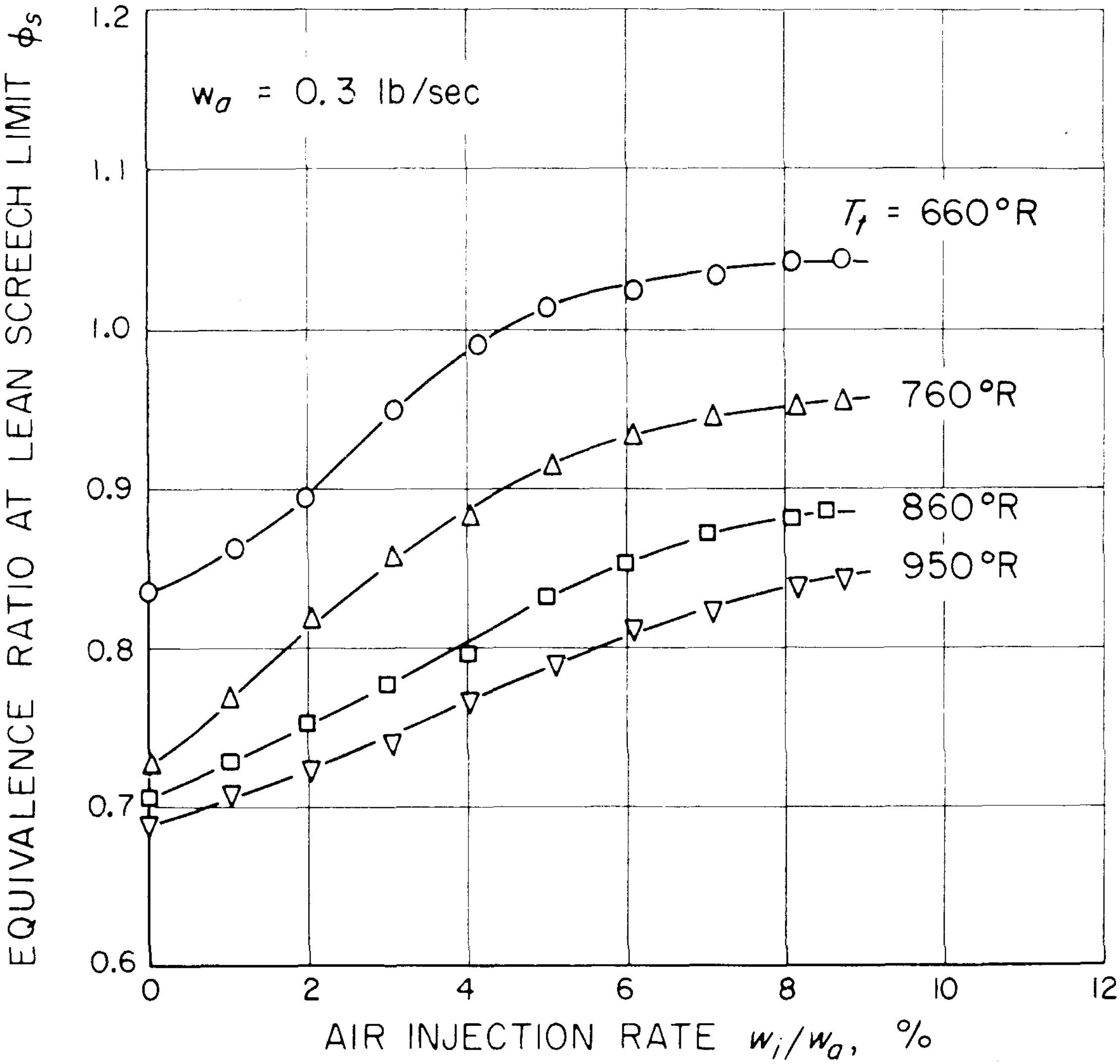



Figure 16 — Effect of air injection on screech limit: Nose injection

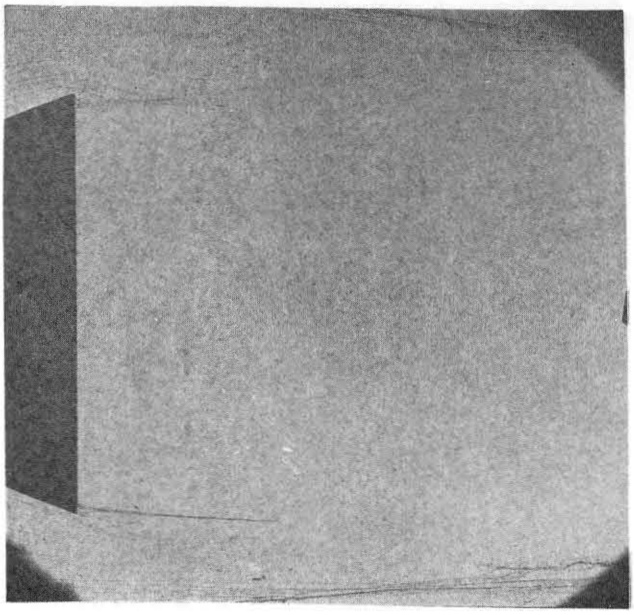


FIGURE 17A — $w_i/w_a$ = 0%

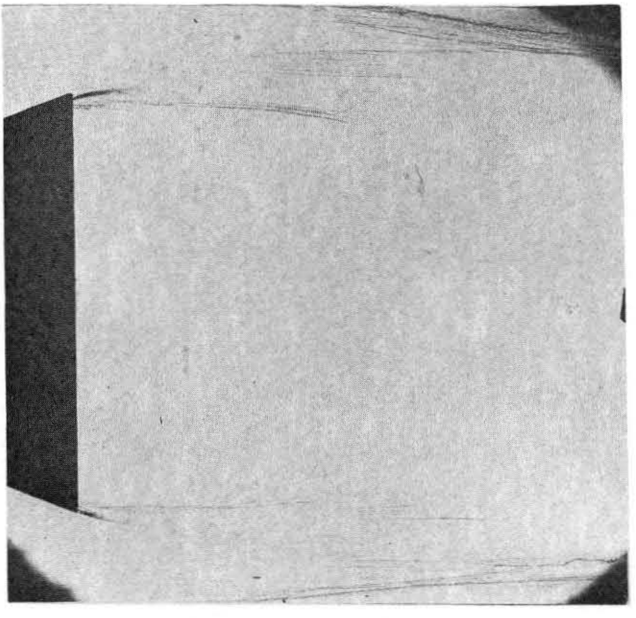


FIGURE 17B — $w_i/w_a$ = 8%

Figure 17 — Schlieren Photographs:
No combustion;
Lip injection

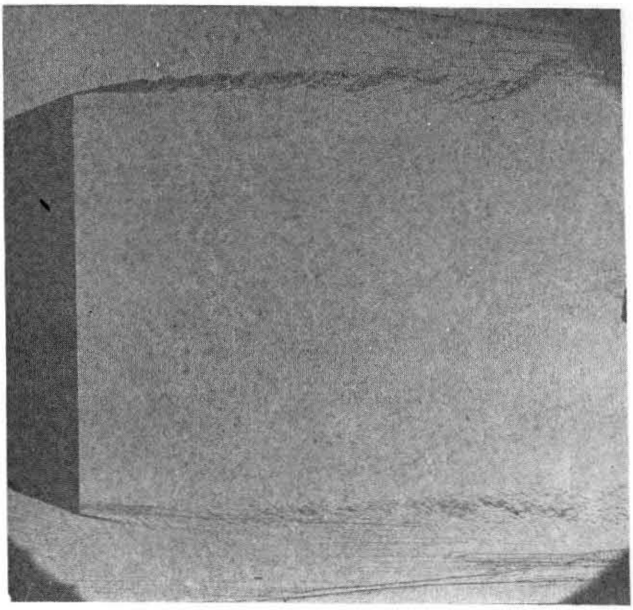


Figure 18A – $w_i / w_a$ = 0%

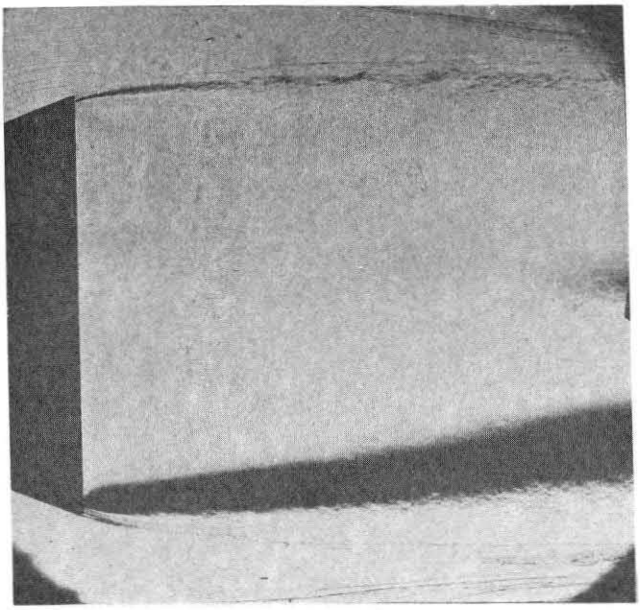


Figure 18B – $w_i / w_a$ = 8%

Figure 18 — Schlieren Photographs:
Smooth combustion;
Lip injection

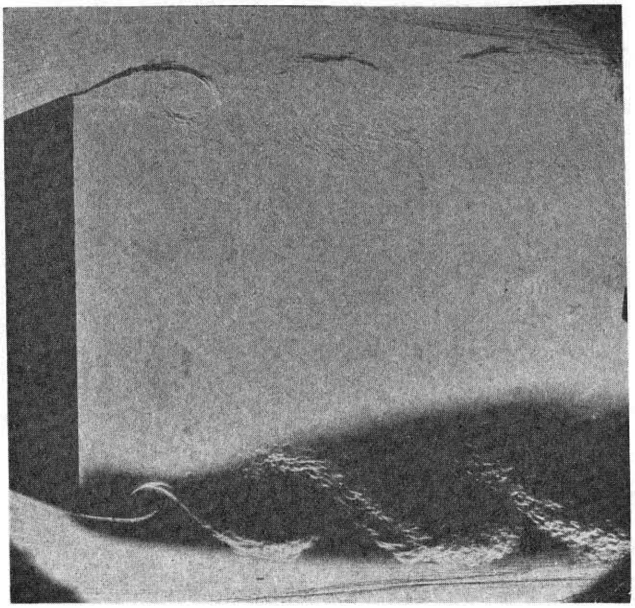


FIGURE 19A — $w_i/w_a$ = 0%

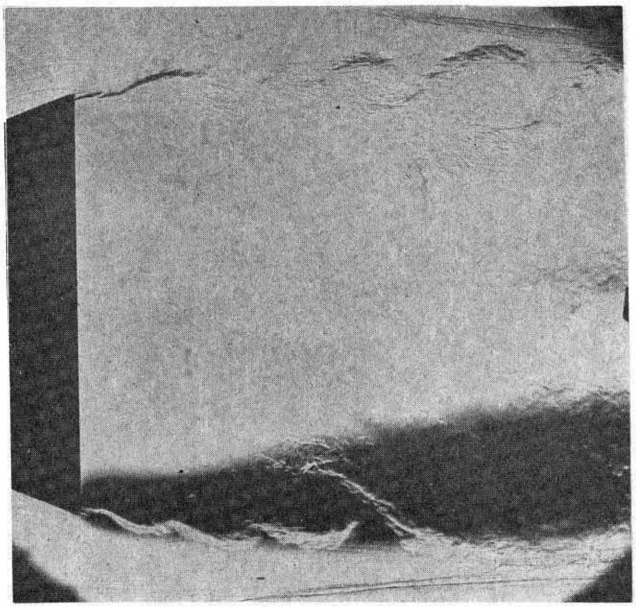


FIGURE 19B — $w_i/w_a$ = 8%

Figure 19—Schlieren Photographs:
Screeching combustion;
Lip injection

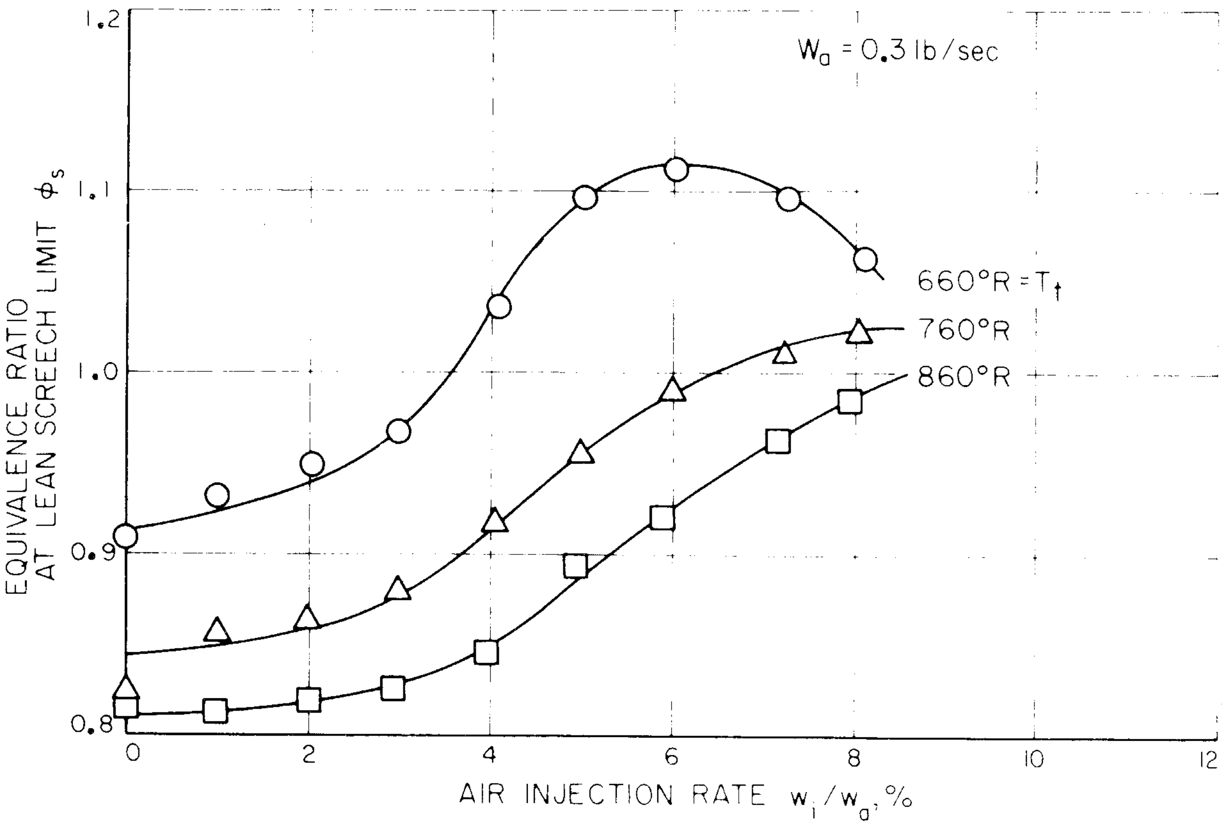



Figure 20–Effect of air injection on screech limit: lip injection

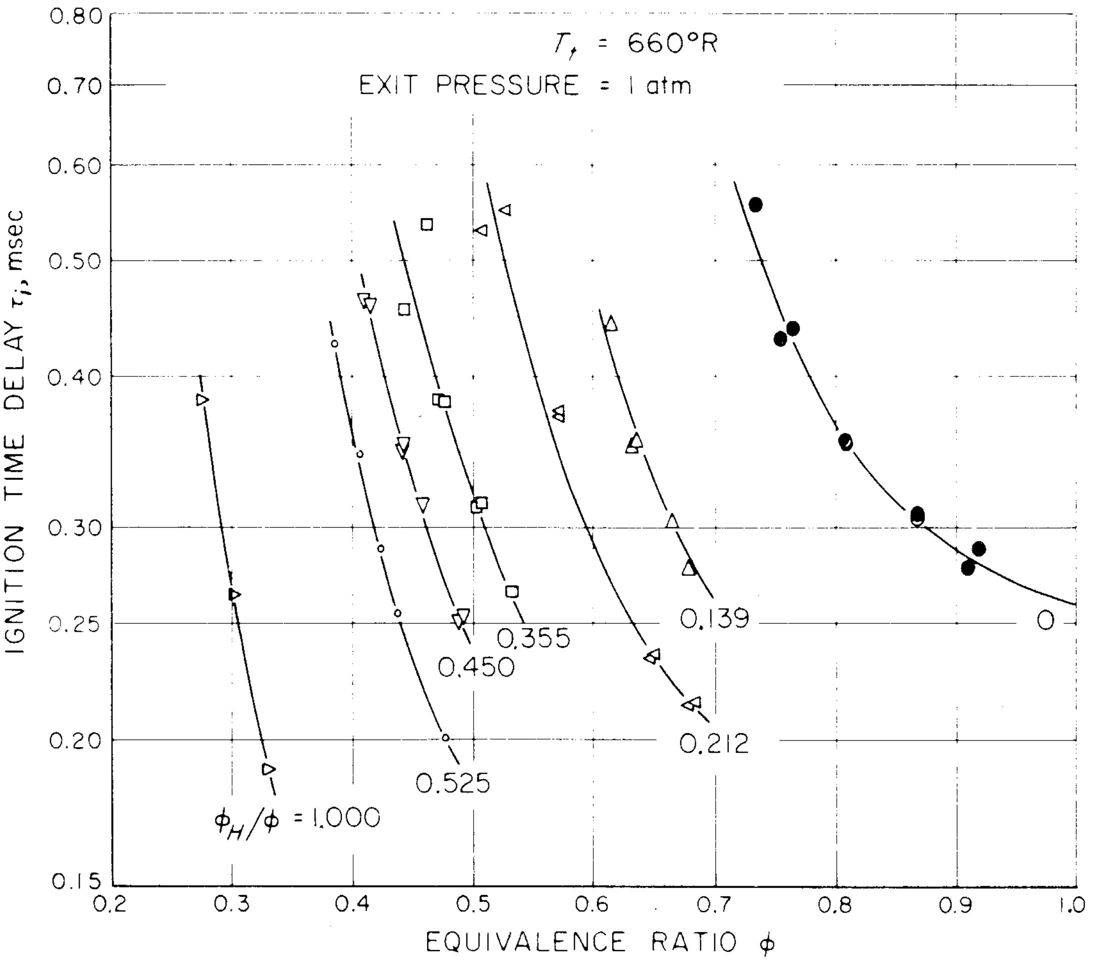



Figure 21— Dependence of ignition time delay on equivalence ratio at various values of hydrogen content

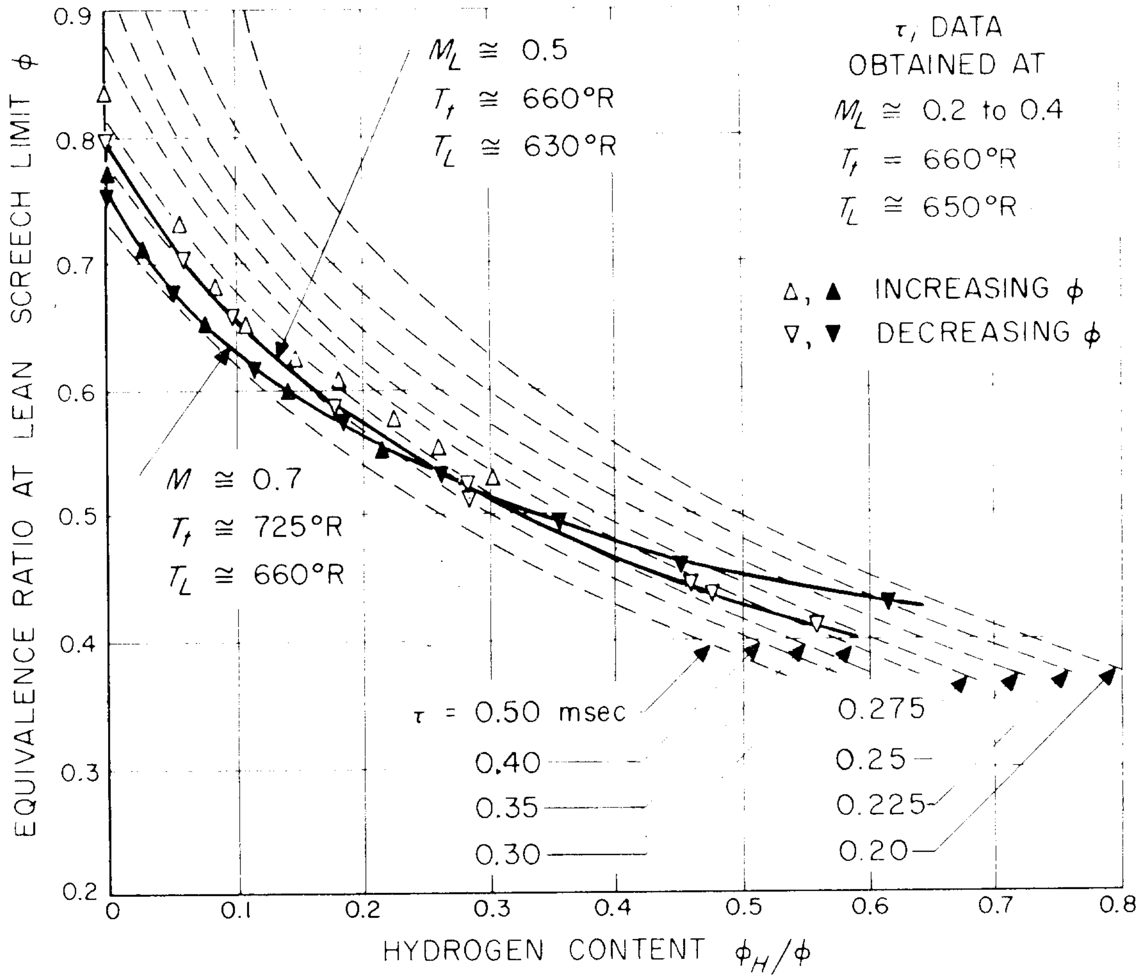



Figure 22—Effect of hydrogen addition on screech limit

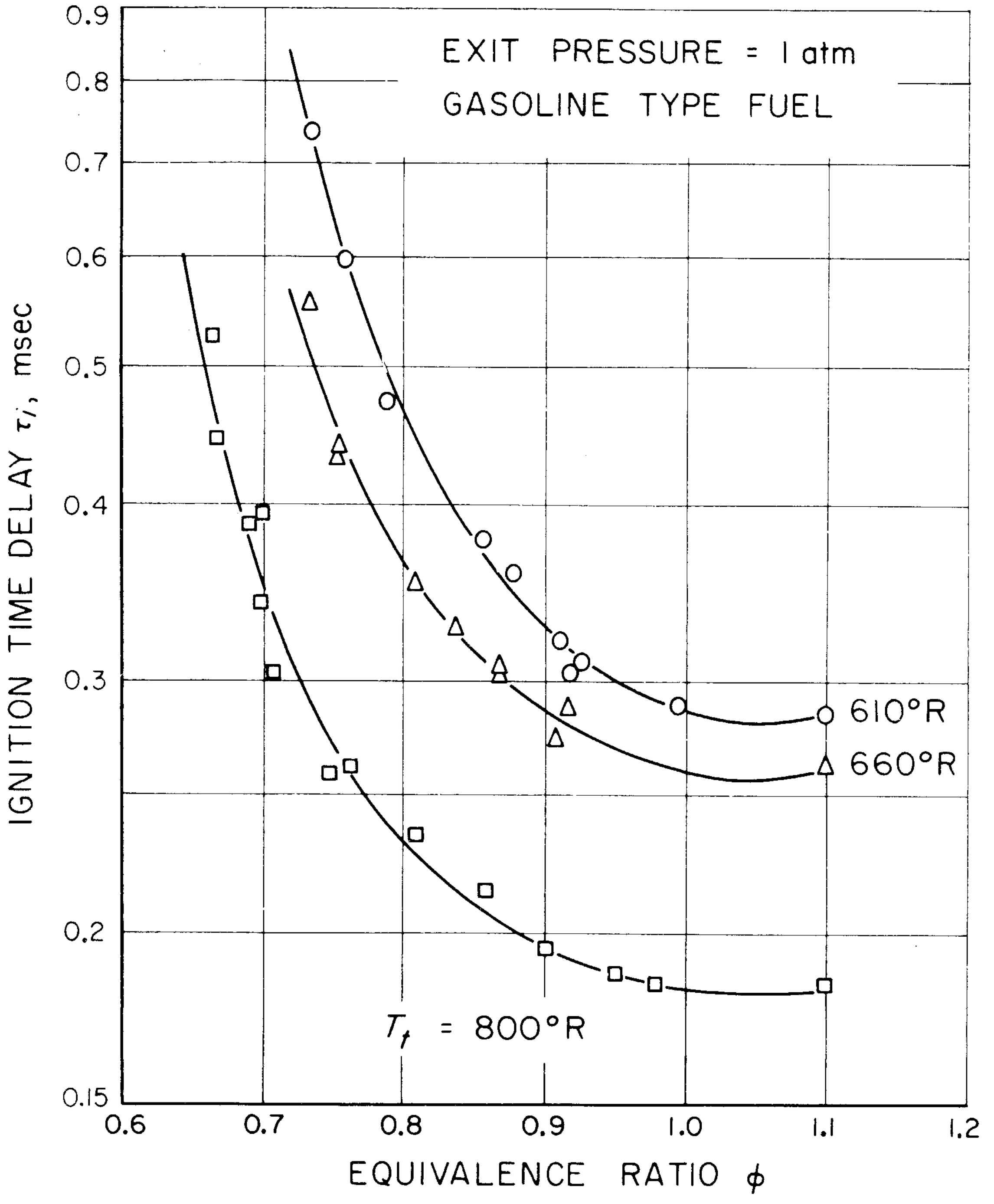



Figure 23 — Dependence of ignition time delay on equivalence ratio at various inlet total temperatures

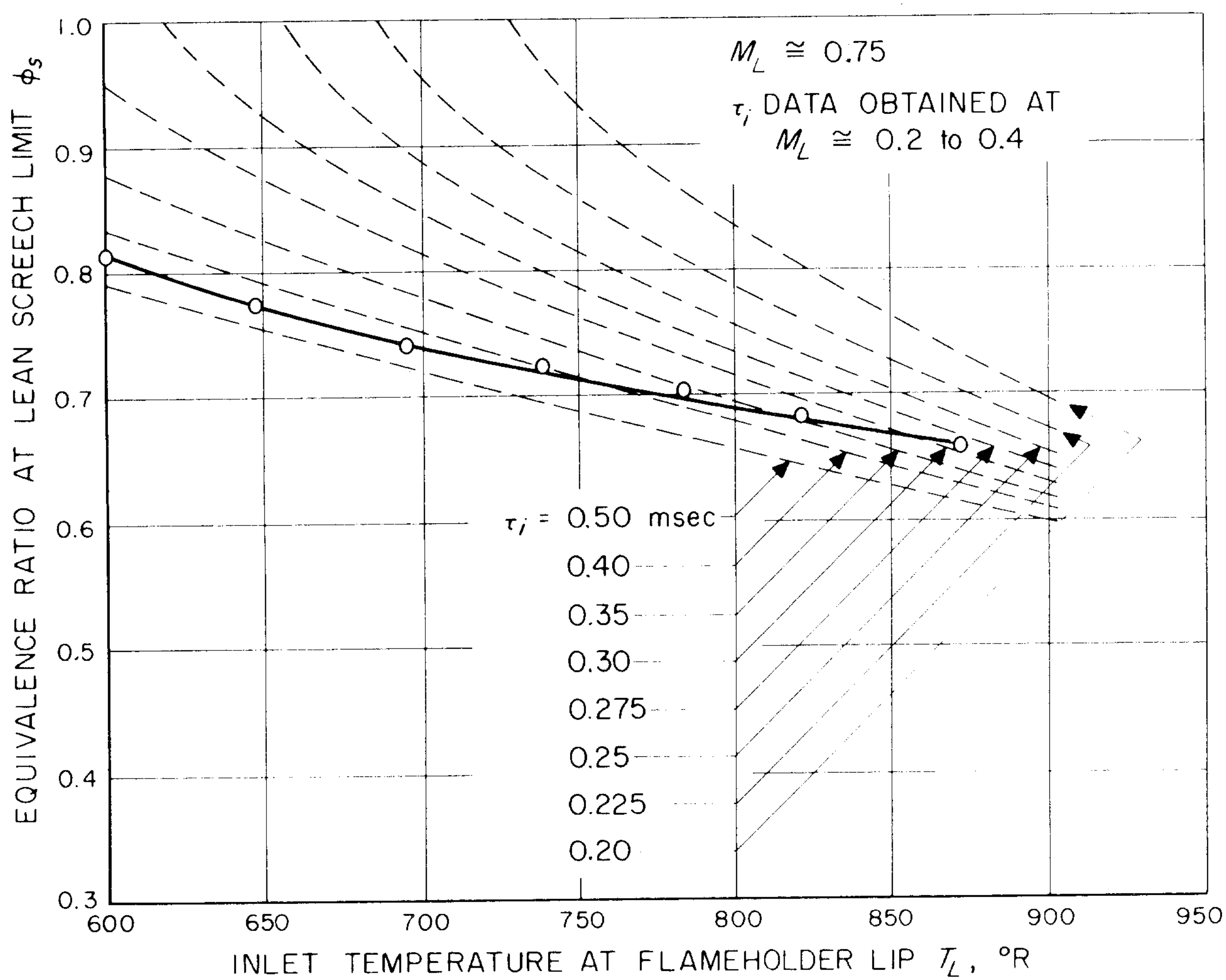



Figure 24—Effect of inlet temperature on screech limit