COMBUSTION AND FUELS RESEARCH

Part I - High-Output Turbojet Combustors

by Wilfred E. Scull and Richard H. Donlon

You have already seen, or will see elsewhere, a portion of the laboratory's research effort on compressors for handling higher air flows. Higher air flows through the engine are necessary to obtain higher thrusts. To go with the compressors of increased capacities, we must also have primary combustors and afterburners which can handle higher air flows, or operate at higher velocities.

A part of our combustion research is aimed therefore at obtaining high performance at high air velocities in the primary combustor, and it is this phase of the work that I would like to discuss now. High air velocities in the primary combustor result in several problems; for example, stable combustion at the air velocities found in present day equipment might be analogous to keeping a match burning in a hurricane.

Combustion at high air velocities must occur with as high a combustion efficiency and as low pressure losses as possible. In general, combustion efficiency may be defined as the ratio of heat output of the combustor to the heat imput of the fuel. Pressure losses are caused by the flow resistance of the combustor liner, and changes in velocity of the air during combustion.

We would now like to demonstrate some results of our research to develop combustors which can operate at high air velocities.

The primary combustor of the turbojet engine consists of a housing and a liner. The liner, which is installed within the housing, shields the combustion space from the blast of incoming air. Here is a portion of a small scale combustor liner typical of present day turbojet combustors. Air is admitted into the combustion space through these series of graduated holes. Fuel is injected through a series of nozzles installed in the upstream end of the liner. We will now operate the upper combustor containing a liner identical to this one. During operation of the combustor, the air velocity will be gradually increased. This gage will indicate air velocity. The blue region on the gage represents the range of velocities over which present-day combustors are designed to operate. If our future turbojet engines are to be capable of propelling aircraft at high supersonic flight speeds, then the combustors of these engines must operate at higher velocities as indicated by the red line on the gage. Combustor pressure loss will be represented on this gage. The brown line corresponds to a maximum allowable pressure loss, above which combustor pressure losses cause excessive engine thrust losses.

This gage will indicate combustion efficiency. The green line represents an efficiency of 100 percent, a desirable value at all operating conditions.

(Commentary during combustor operation):

We will now operate the combustor. (The air velocity and fuel flow will be increased simultaneously to maintain a constant fuel-air ratio...) Combustion is now established.

Notice that the combustion efficiency remains high, although less than 100 percent, as velocity is increased. Notice also that the combustor pressure losses are below the maximum allowable value, and increase with increasing air velocity... Eventually, as air velocity increased further, combustion blow-out occurred before the future required value of velocity was reached.

Now let us depict the performance of the combustor on charts. On this chart (C-35902), air velocity in the combustor is represented on the horizontal scale; the shaded blue band corresponds to the blue region on the velocity gage. The vertical red line corresponds to the air velocities required in future engines. The vertical scale represents combustion efficiency, with the horizontal green line corresponding to the 100-percent value on the efficiency gage. This curve represents the combustion efficiency of our typical present-day combustor which we just operated. The combustion efficiency was somewhat below 100 percent, decreased progressively as air velocity was increased, and combustion blow-out occurred at a velocity less than our future required value.

On this chart (C-35916), air velocity is again represented on the horizontal scale. The shaded blue band and the vertical red line represent the same velocities as on the first chart. The vertical scale represents combustor pressure losses, with the horizontal brown line corresponding to the maximum allowable pressure loss. This curve represents the pressure losses of our small-scale combustor. Pressure losses increased as air velocity was increased, but remained below the maximum allowable level long before the future required value of velocity was reached.

This combustor is typical of combustors which have been available for some years. These combustors are satisfactory for the flight speeds of today. However, at higher future flight speeds, combustors of improved design are necessary.

Now we would like to demonstrate a combustor which incorporates design features obtained from an over-all combustion research program. An experimental liner designed to operate at high air velocities is installed in the lower small-scale combustor housing. The air entry arrangement and fuel nozzle configuration have been modified to obtain an optimum design for high air velocities. As a result of these modifications, this combustor can operate at higher combustion efficiencies at any given value of air velocity than the previous model. In addition, the experimental liner is thinner than the preceding one, and the size of the combustion space has been reduced. This change was necessary to reduce the combustor pressure losses which would otherwise become excessive at high values of air velocity. We will now operate the lower combustor. The upper and lower combustors are similar, differing only in the liners. These same gages will indicate air velocity, combustor pressure loss, and combustion efficiency.

(Commentary during combustor operation):

Combustion is now established. The air velocity and fuel flow are being increased simultaneously as in the first demonstration. Notice that the combustion efficiency remains near the 100-percent value as air velocities are increased, and velocities in excess of the red line future value are attained without incurring combustion blow-out. Notice also that the combustor pressure losses do not exceed the maximum allowable value until the future required value of velocity has been reached.

We can now show the performance of our improved combustor on our charts (C-35902 and C-35916). The combustion efficiency was substantially 100 percent until values of velocity in excess of the required value had been attained. Combustor pressure losses increased progressively with increases in air velocity, but remained in the allowable range until our future required value of velocity had been exceeded.

This demonstrates our research on turbojet combustors to obtain the improved performance at the high air velocities necessary in turbojet engines capable of propelling aircraft at high supersonic flight speeds.

Mr. __________, our next speaker, will now describe some of our fuels research as related to the afterburner of the turbojet engine.

Part II - Special Fuels

by Irving A. Goodman and Eugene E. Dangle

The afterburner of the turbojet engine is shown in the engine diagram (overhead). Fuel is sprayed into the hot gas leaving the turbine. The exhaust jet becomes hotter, its velocity higher, and the engine thrust is increased. Although the afterburner is not intended for continuous operation, it is nevertheless a very vital part of any propulsion system when extra thrust is required, as for example, during take-off, climb, and acceleration.

As with the primary combustor of the turbojet engine, much of our effort in afterburner research is aimed at obtaining good performance at increased air velocities through the combustor. One technique for achieving this is the development of improved afterburner designs. We therefore do research on afterburner design which parallels that just described by Mr. ________ for the primary combustor. The problem in the afterburner is in some ways more severe than in the primary combustor. Because of the pressure drop which occurs across the turbine, the pressure in the afterburner is lower and the velocity is higher than in the primary combustor. This makesit more difficult to obtain efficient combustion in the afterburner. Consequently, we may not be able to go as far as we would like in achieving better afterburner performance by means of design changes alone. Another promising technique for improving performance is the use of special fuels which will burn more efficiently in the afterburner at these severe high-velocity conditions. Such fuels may also be used to good advantage in the ramjet combustor wherein we again encounter very high velocities and low pressures. I should like to discuss here one phase of the research devoted to the development of these special fuels.

A part of our fuels research involves the evaluation of the fundamental combustion properties of various materials. For example, the so-called fundamental speeds of fuels are evaluated in an apparatus similar to the one you see here. These flame speeds are indicative of the chemical reactivity or ease of burning of the fuel. The higher the flame speeds, the higher the efficiency with which the fuel should burn under severe operating conditions.

This apparatus consists of a simple Bunsen-type burner analogous to that in common use in most chemistry laboratories. This burner is provided with a means of metering the fuel and air flow through it. By means of a special light source located behind the panel (open shutter), we can project a shadowgraph image of the flame onto the screen to the right of the stage, as shown here, or onto photographic film. The projected area of the flame is measured, and the volumetric flow of gases through the burner divided by the actual flame area can be used to calculate the fundamental flame speed.

The fundamental flame speeds differ considerably for different fuels. Propane, which has a flame speed of about 1.27 feet per second as indicated by the first bar graph (C-36103) has the molecular structure indicated by this model. Each black sphere represents a carbon atom and each yellow sphere a hydrogen atom. A molecule of propane consists of three carbon atoms connected together in a chain, with hydrogen atoms connected to each of them as shown by the yellow spheres. Propylene, which has a somewhat higher flame speed, about 1.44 feet per second, as indicated by the second bar graph, has a slightly different molecular structure. By removing two hydrogen atoms from adjacent carbon atoms of our propane model we obtain this model of a propylene molecule, wherein two of the carbon atoms are now joined by a double bond. This double bond between the carbon atoms is less stable than the single bond which existed in the propane molecule. It is therefore a weak point where oxygen of the air can more easily attack the molecule during combustion. Because of this weak link, propylene burns more readily and has a higher flame speed than does propane.

Propylene oxide has a still higher flame speed, about 2.29 feet per second, as shown by the third bar graph. Its molecular structure may be represented as resulting from insertion of an atom of oxygen, represented by this red sphere, by partially breaking the double bond of the propylene molecule. This molecule, in which partial oxidation has already taken place, is even more vulnerable to further oxidation and hence it burns very readily and has the high value of flame speed noted.

Thus the flame speed of a fuel is seen to be dependent on the molecular structure of the fuel. By synthesizing new fuels having the desired molecular structures it is therefore possible to obtain higher flame speeds. A part of our research effort is devoted to the synthesis of such fuels. These are then evaluated in an apparatus like this to determine their flame speeds. The more promising fuels are further evaluated by testing them in jet engine combustors.

The flame speed of ordinary jet fuel, which is a blend of various hydrocarbons, is about 1.12 feet per second, as indicated by the final bar graph. Propylene oxide, at 2.29 feet per second, is seen to have a flame speed approximately double that for jet fuel. Because of the better burning characteristics of propylene oxide, we would therefore expect it to provide more stable, efficient combustion at higher velocities than does jet fuel. We shall now demonstrate the performance obtained with these two fuels. First we will burn jet fuel and then we will burn propylene oxide in the small 2-inch-diameter ram jet combustor located behind the window. The center gage above the window will indicate the air velocity through the combustor.

The combustor is now operating on jet fuel, and the air velocity is being progressively increased. Using the jet fuel, blow-out occurred at this value of air velocity. We shall now switch to propylene oxide.

The combustor is now operating on propylene oxide. Again velocity is being increased. With propylene oxide, which has the high flame speed previously noted, blow-out did not occur until a considerably higher air velocity was reached, approximately twice that observed for jet fuel.

Thus special fuels having higher flame speeds give us one promising means of obtaining good performance in ram jets and in turbojet afterburners at increased air velocities. The propylene oxide which was demonstrated here is by no means the most promising fuel available for this use. It was used here merely as an indication of the possibilities which exist in the use of special fuels.

With the development of high-performance afterburners that burn to high outlet temperatures and operate at increased air velocities, a special problem has arisen -- the problem of afterburner screech. The next speaker, Mr. __________, will discuss this problem. Rayle

Part III - Afterburner Screech

by Warren C. Rayle and Leonard K. Tower

When a turbojet engine propels an aircraft at supersonic speed, the gas flows into the afterburner at pressures and temperatures considerably higher than those for lower flight speeds. This does not hinder the combustion process -- quite the contrary. Efficient combustion is not too difficult to obtain either through combustor design or the use of special fuels. Even efficient combustors have been found at times to operate unstably. One form of instability is descriptively termed "screech."

This phenomenon -- which also is found in rocket and ram jet engines -- is typified by a shrill, intense, and sometimes even musical sound. In a particular burner, the pitch, or frequency, remains nearly constant.

This violent sound is accompanied by other effects. The combustion efficiency usually rises when screech begins. No one would object to this; however, the burner itself all too frequently disintegrates. The first slide (C-31832) shows an afterburner liner which has been damaged by screech. The thin metal has broken completely away. Such damage may result from two causes: (1) the pressure fluctuations may fatigue and crack the metal; (2) the hot gas scrubbing back and forth may raise the temperature until the metal weakens or melts.

Screech is then a serious problem. These destructive tendencies must be eliminated.

In studying this problem, small models as well as full-scale afterburners are used. Such a small unit is mounted in the adjacent test cell and can be seen through the window (left). It comprises a simple 6-inch-diameter duct connected to a single can-type turbojet combustor. Thus the gas entering our small afterburner is made to resemble that entering the full-scale unit. Into this stream of hot gas, fuel is sprayed and ignited. The resulting flame is seated or stabilized on a conical flameholder such as this one. The flameholder can be moved back and forth along the duct. Its position is indicated by the green marker on the outside of the duct.

The two lower dials above the window will show the temperature of the duct and the thrust produced by the afterburner. Operation will begin with the flameholder in the downstream position. At this condition there will be no screech; there will also be very little thrust, since most of the flame will be outside the duct. The flameholder will be drawn upstream until screech is encountered. As it moves upstream, the thrust and temperature will increase. When screech commences, both will increase sharply. (Demonstration)

Notice that this burner is still in one piece. However, it is ruggedly built, and was exposed to screech for but a short time.

The problem of screech can be approached in two steps -- first we must find out just what is happening -- then we can deduce why it happens and what can be done about it. To start with, we may infer from the constancy of the screech frequency that the oscillation involves an acoustic resonance of the duct. Saying this does not solve anything, since there are very many ways in which such a resonance may exist. The following movie (animation, black and white) shows the gasmotion for three types, or modes, of resonance. The longitudinal mode is that which occurs in an organ pipe. The radial mode might be simulated by dropping a lump of sugar in a cup of coffee. The transverse, or sloshing mode, finds the gas moving first to one side of the duct, then to the other. (Movie off)

As you saw, each mode of oscillation has its own peculiar pattern. If, then, we wish to identify precisely just which mode is present in a screeching burner, we can do so by exploring the sound field within. To accomplish this, a special instrument was designed. This probe microphone (upper left of stage), watercooled, may be inserted directly into the combustion zone of a screeching burner. The sound, picked up at the tip, is transmitted out the tube to a microphone.

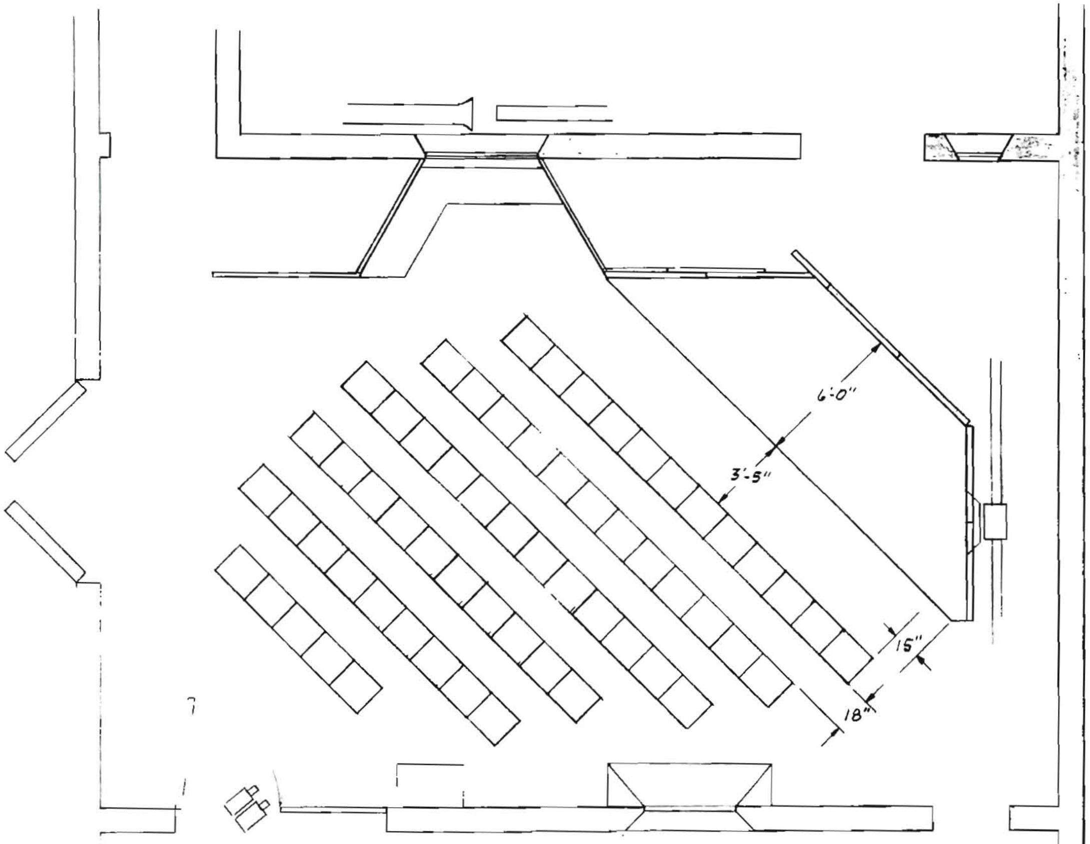
After we have found the mode of resonance in the burner, we would like to discover just where the flame is located and how it is moving. The instrument used for this is the ionization probe.

Another factor in thecause and cure of screech may be the rate at which heat is released by the flame. A third instrument, a photocell probe, permits measurement of the instantaneous brightness of the flame. Light enters a tiny hole at the tip, travels along the tube to a photocell.

These instruments all provide electrical signals. They can be connected to an oscilloscope for observation or photography; they may also be recorded by a tape recorder and studied later.

Through the use of such instruments as these, in apparatus ranging from the full-scale afterburner to such small-scale models as that demonstrated here, we have been able to identify modes of resonance accompanying screech. In addition, means by which screech can be prevented have been designed and tested.

This concludes the discussion of a portion of our combustion and fuels research. We have not attempted to be comprehensive, but have described briefly three of the main problems involved in improving the performance of the turbojet engine.



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LEWIS FLIGHT PROPULSION LAB.

SCALE 1/4" = 1'-0"

WHH 5/18/54
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FUELS & COMBUSTION RES. DIV.
PROJECTOR to SCREEN - 31' - SEAT WIDTH - 20"

Ⓐ REVISED - PROJECTOR DIST. 31' 5-21 r.l.

NACA

C-36016


PIPE TEMPERATURE
VELOCITY
THRUST
SCREECH INSTRUMENTATION
COMBUSTION AND FUELS RESEARCH
EFFECT OF AIR VELOCITY ON COMBUSTION EFFICIENCY
EFFECT OF AIR VELOCITY ON PRESSURE LOSS
CURRENT
EXPERIMENTAL
AIR VELOCITY
MAX. ALLOWABLE
COMBUSTOR PRESSURE LOSS
COMBUSTION EFFICIENCY

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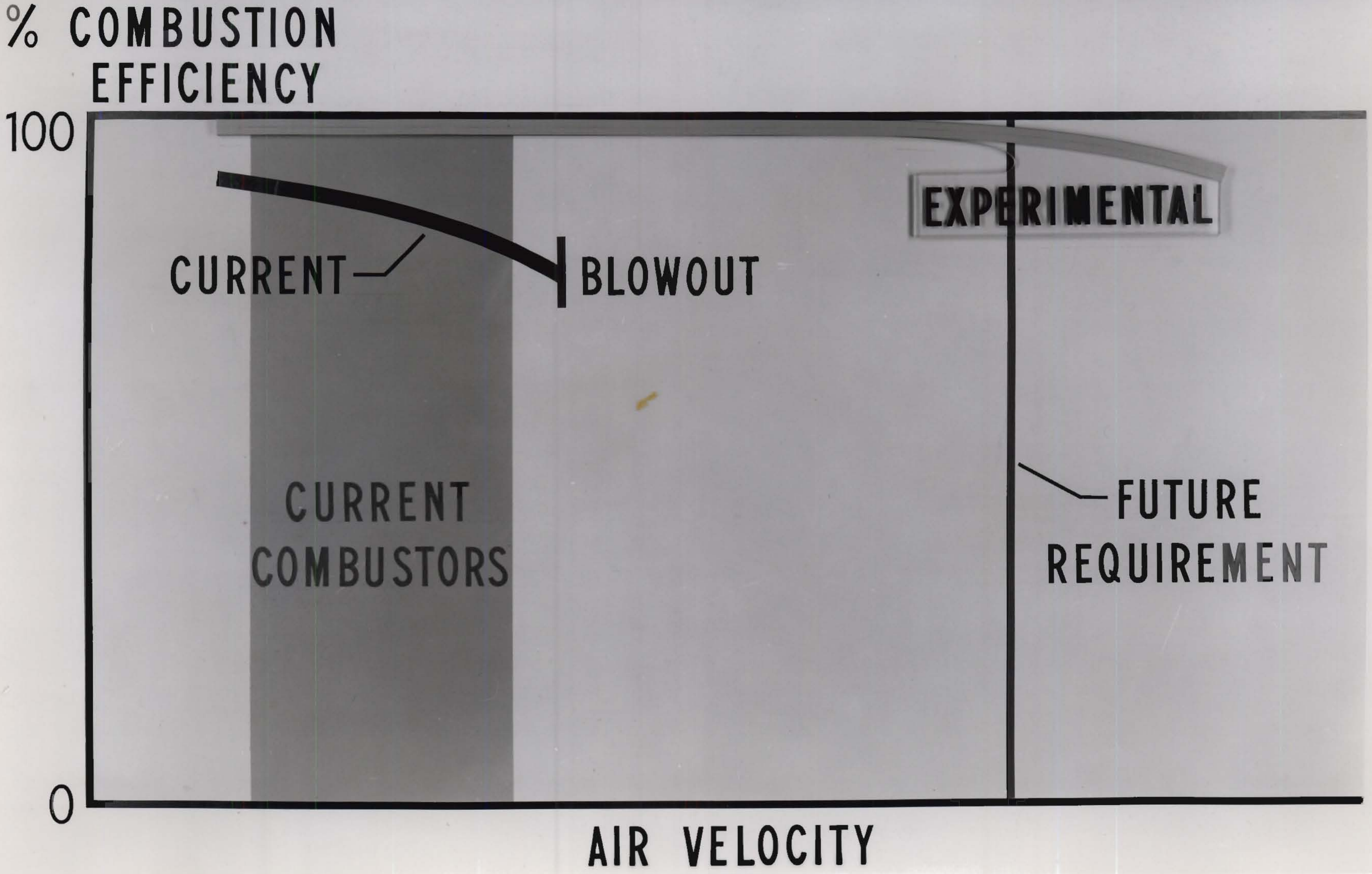
EFFECT OF AIR VELOCITY ON COMBUSTION EFFICIENCY



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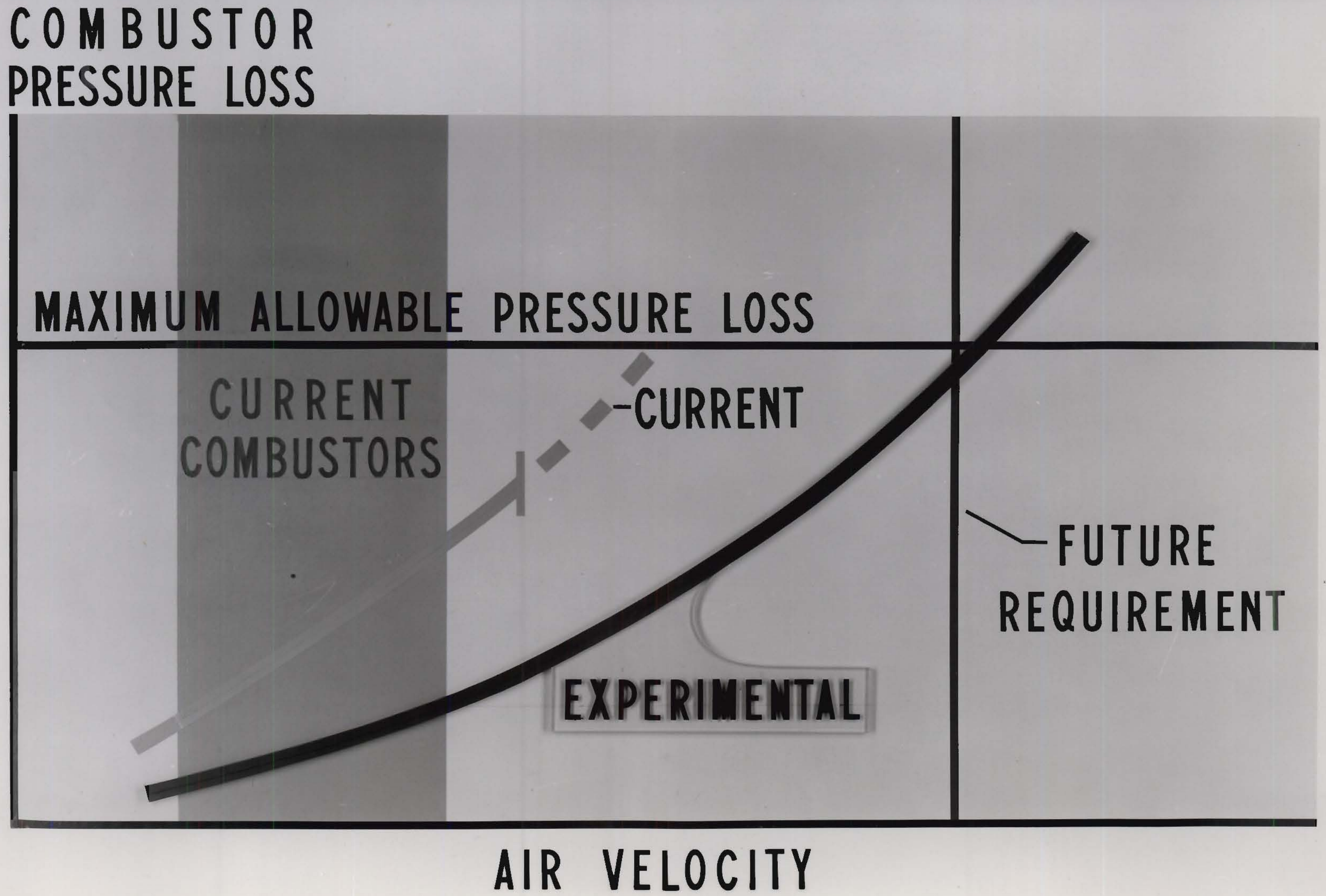
EFFECT OF AIR VELOCITY ON PRESSURE LOSS



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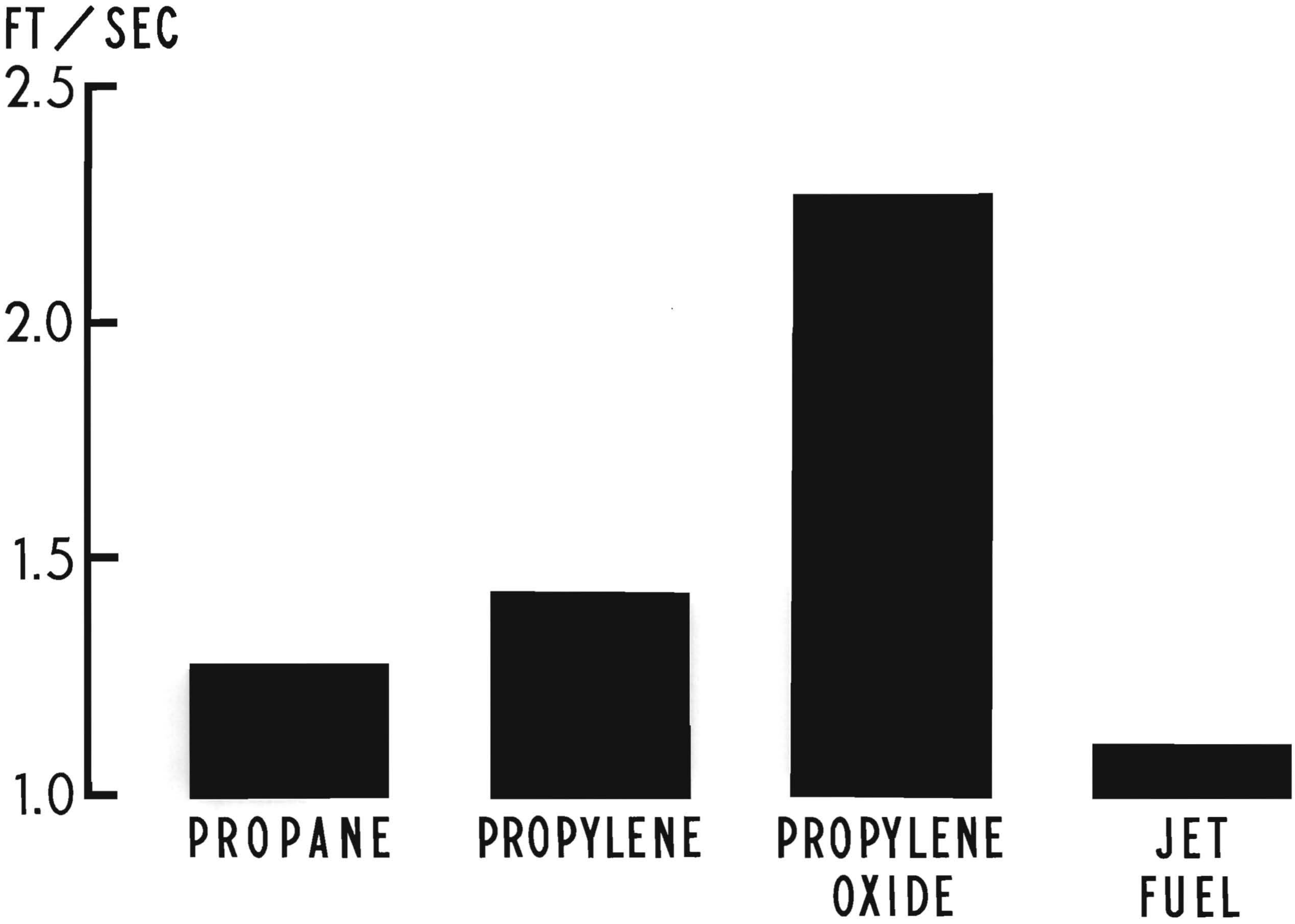
C-36103

FLAME SPEEDS



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