COMBUSTION RESEARCH

Proposed Talk for 2nd Annual Inspection, FPRL, September 1948.

INTRODUCTION

It is intended here to tell you the scope and nature of the combustion research at NACA and to indicate the status of results in this field.

Combustion as related to aircraft propulsion is the conversion of chemical energy stored up in the fuel to heat energy that can be converted to useful power. The major combustion problem in all jet and gas turbine engines is to generate efficiently tremendous quantities of heat energy from the fuel in a small volume and in a short space of time. Just for example, present-day gas turbine combustors such as these (point to display), release about the same amount of heat that a large steam locomotive does. There are, of course, important attendant problems. Loss of engine cycle pressure in the combustion system must be kept low. Combustion equipment should be light weight and durable. Flexibility of operation, especially at "off-design" points is desired. And there are still other problems. As is so frequently the case in engineering, compromises are required in the satisfactory solution of all of these problems, some of which are conflicting. To illustrate the sort of work that we are doing currently, we shall discuss some of these problems as they are encountered in different combustion systems.

RAM JET COMBUSTION

Consider first, for example, combustion in one of the least mechanically complicated systems - the ram-jet engine. As you know, the ram-jet is that celebrated "flying stovepipe" (Fig.23). The ram-jet must be launched and accelerated by some external means. When the ram-jet is up to speed, its forward motion is used to gather air and this air is compressed by being slowed down from supersonic through the speed of sound to subsonic velocity in a diffuser, a section of duct that is first contracting and then expanding.

It is this "ramming" of the air into the diffuser that gives us the compression that any heat engine needs. In your automobile, a piston performs this function. The compression ratio in a ram-jet depends on its speed; it should be a little less than two to one at the speed of sound, and will increase to about eight to one at twice the speed of sound and to about thirty-six to one at a flight Mach number of three. Fuel is sprayed into the compressed air here. The fuel mixes with the air and burns here on a flameholder that we will discuss later. The hot gases expand terrifically and since they can't flow out against the high pressure "rammed" into the engine, they flow out at very high velocity into the low pressure region of the exhaust nozzle. The resulting momentum of this exhaust jet drives the engine forward. (Show all this on Fig.23). Simple, No moving parts.

Although the air inside the ram-jet is slowed down, it isn't stopped. Fuel must be burned efficiently in an air stream flowing at as much as 300 feet per second, and in mixtures near chemically correct where the highest possible temperature is obtained.

Now most flames can be blown out. (Light a match and blow it out). Some easily. You must do more than spray fuel into an air stream and light it to have a ram-jet combustor. Here is an air-duct with a window, a fuel spray, and a spark-gap for ignition. This gage tells the air velocity into the duct. Note how easily the flame is blown out of the duct and at low air velocities. (Demonstrate by increasing velocity to blow-out. Note where the gage stopped - 50 feet per second.

Introduction of a flame holder, such as this one (show), by creating turbulence and stagnant regions permits flame to be held to much higher air velocities. Because it has no mechanical compression, but depends only on ram, the ram-jet cannot tolerate much loss of its hard-won cycle pressure in the combustion process. Nevertheless, something like this is needed to hold the flame in there.

The gases are hot enough to heat this metal rod to incandescence quickly. Blow-out is possible, but at high air velocity. (Demonstrate by increasing velocity to blow-out). Note where the gage stopped - 180 feet per second.

Right here is the problem: To maintain efficient combustion at velocities of as much as several hundred feet per second but without blocking too much of the duct. This is desired so that high thrust can be obtained. This chart for a typical ram-jet combustor amplifies the situation (Fig. 24) The plot is the velocity of the air entering the combustor versus the fuel air ratio - lean here, rich here. The curves are the blow-out limits of a typical ram-jet at a simulated flight Mach number of 1 at sea level and at 10,000 feet. In this area, combustion can be maintained, in this area, blow-out occurs. For any given inlet conditions, a limited range of fuel-air ratios where operation is possible exists. Stable combustion over a range of fuel-air ratios is desired so that operation over a range of thrusts and speeds is possible. Note how much narrower the operable region is at altitude. By utilizing variable pressure and variable temperature air supplies and low pressure exhaust systems such as exist here at Cleveland ram-jet combustion can be studied over the entire speed-altitude spectrum of interest. The problem is to widen the operational limits for the ram-jet combustor, and especially to keep them from shrinking at altitude, by discovering and then applying appropriate design rules.

High combustion efficiency is also desired so that range will not be shortened by wasted fuel. This chart (Fig 25) shows combustion efficiency plotted against fuel-air ratio at sea level and at 10,000 feet. Combustion efficiency decreases as altitude increases and as the air for combustion gets thinner and colder. Again the problem is that of learning design criterions for flame holders and fuel injectors that will result in high combustion efficiency. Here are some examples of the types of combustor that have been investigated. (Display).

One further ram-jet problem is created by the fact that enormous quantities of air are required for research and development of full scale combustors. Although this laboratory has sufficient air handling capacity now to do research on full-scale ram-jets, industry does not have such facilities. Consequently, it is important to know whether design principles that work in small units will be applicable in large units. Scale and similitude are being investigated in 4, 8, 12, and 20-inch diameter combustors.

Now that we have considered a mechanically simple combustion system, Mr. Childs will continue the discussion with a consideration of some combustion problems encountered in a different sort of system - the aircraft gas turbine. Mr. Childs.

GAS-TURBINE COMBUSTION

The combustion problems encountered in gas-turbine engines - turbojets, and turbopropeller engines are not all the same as the problems in ram-jets. In the turbine engine as in the ram-jet, fuel must burn efficiently in a high-velocity air stream with low pressure loss, but some really big differences exist. For example, the combustor outlet temperatures in the turbine engine must not exceed values harmful to the turbine blades. This is in contrast to the ram-jet, where final temperatures are required which are about three or four times as high as for the gas turbine. The relatively cooler combustor-outlet gases of the gas-turbine are achieved by rapidly mixing dilution air with the combustion gases before the gases enter the turbine. In general, all gas turbine combustors operate on the same principle.

Figure 26 shows a cross sectional view of a typical gas turbine combustor. This combustor is situated downstream of the compressor and upstream of the turbine. One of the turbine blades is shown. Air enters at the upstream end of the combustor and passes into the combustion zone through many perforations in this liner. Fuel is injected in a fine spray by means of an atomizing nozzle. The air which enters at the upstream end of the liner serves to burn the fuel and is called primary air. The secondary air which enters farther downstream serves to dilute the combustion gases and reduce their temperature to values which can be tolerated by the turbine blades. The passage of the air through these perforations results in pressure loss, but because compression is performed mechanically, more pressure loss is acceptable in a turbine engine combustor than in a ram-jet combustor.

On your right are combustors from some actual gas turbine engines. This is a can-type combustor, disassembled so that you can see the component parts: the fuel nozzle, the liner, and the housing. Several of these cans arranged around the compressor-turbine shaft constitute the complete combustor in the engine. This is a combustor liner similar to those used in gas turbine engines but made especially to fit into our combustor housing. A liner identical with this, but having one side cut away so that you can better view the combustion process, has been installed in our combustor housing. The fuel spray nozzle extends through this hole and the spark plug extends through this hole. The liner which is installed is in this position and air flow is in this direction. This combustor will be operated to illustrate the gas turbine combustion process.

The combustor is now operating at conditions which are typical of those encountered in a gas turbine engine. The velocity is somewhat lower than the velocity attained with the ram-jet combustor. Note the short flame length. Little or no burning occurs downstream of this plane. Most of the burning occurs in the upstream end of the combustor. The principal process occurring in the downstream end is mixing of the dilution air with the hot combustion products. This short flame length is required in this type of combustor because the combustor must be short in order that the shaft connecting the compressor and the turbine will in turn be short and therefore of light weight. This type combustor normally gives a higher combustion efficiency than a ram-jet combustor. This higher combustion efficiency and shorter flame length result in part from the high degree of turbulence which is created in the combustion zone by passage of jets of air through the holes in the liner. Note the turbulence in the flame zone.

Early research at this laboratory on gas turbine combustors was aimed at finding the causes and cures for low-altitude operational limits and low combustion efficiency. This first phase of gas turbine combustor research has been successful to a large degree. Some of you will recall our summary of this work at last years inspection. However, another problem was aggravated in the process. That is the problem of maintaining a preferred temperature profile across the combustor outlet. A consideration of the stress along a turbine blade as a result of centrifugal force and the strength of the blade material at different temperatures leads to a preferred temperature distribution from the blade root to tip of the sort shown in figure 27 . Temperature is plotted on this axis. This point corresponds to the root of the blade; this point corresponds to the tip of the blade; various points in between represent corresponding positions along the length of the blade. The temperature which the blade can withstand increases progressively from the root toward the tip of the blade, with a decrease in temperature at the tip in order to avoid overheating the engine housing. This is what we want. An example of an undesirable temperature distribution is shown on the upper potion of this figure. This is what we don't want. A temperature distribution of this sort frequently leads to blade failure. This incorrect distribution of temperature is easily encountered. With incorrect distribution of temperature into the turbine, either the life of the engine is shortened, or its thrust will be lowered and its fuel consumption increased as a result of the engine being operated at lower temperatures to avoid turbine failure. Currently, effort is going toward finding design criterions that when applied will help to product this correct distribution of temperature. This research has been successful in that several methods have been devised for obtaining the desired temperature distribution. As indicated here, changing the shape of the perforations which admit the secondary air is one method of obtaining the correct temperature distribution.

Also active at present is an investigation of fuel sprays and the role of fuel atomization in gas turbine combustor performance. Figure 28 illustrates and points up one of the problems. Combustion efficiency is plotted against temperature rise through the combustor. The chart is for a turbojet combustor operating at high altitudes, a severe condition for good combustion as is noted by the generally low values of combustion efficiency shown. A fixed value of temperature rise is required for each flight condition, with high temperature rise required for high engine rotor speeds. At low temperature rise, highest efficiency is obtained with a small nozzle, whereas high temperature rise cannot even be obtained unless a larger fuel nozzle is used. Therefore, in an engine, where this entire range of temperature rise must be covered, the need for a variable fuel nozzle is evident. This is only one of several significant findings to come from this study so far, but it is illustrative of our results.

TAIL PIPE BURNING

Although we have discussed the primary combustion process for turbine engines, auxiliary combustion is also of interest for special applications. For example, by burning fuel downstream of the turbine of a conventional turbojet engine it is possible to obtain higher gas temperatures in the exhaust jet than can be withstood by the turbine. This increases the thrust of the engine. Thrust augmentation by tail-pipe burning, as it is called, is useful for take-off, emergency bursts of power, and supersonic flight.

The combustion problem in tail-pipe burning is similar to that of the ram-jet - retention of flame in a high velocity gas stream. The problem differs from that of the ram-jet in that combustion occurs in an air stream that is hot, about 1200° F, and that has been altered in composition by partial consumption of the oxygen in the primary combustion process.

Operational characteristics and design factors of tail-pipe combustion systems are being studied in full scale engines operated in the altitude test facilities of the laboratory. Figure 29 illustrates one of the problems encountered: blow-out at altitude. Altitude is plotted against flight Mach number. ~~which is merely the speed of sound.~~ This curve separates the range of flight conditions where the tailpipe burner would blow out from the range of flight conditions where burning could be maintained. This curve shows the operational limits obtained with one of the early tail-pipe burners investigated at this laboratory. We are currently engaged in the project of increasing this altitude operational limit.

We will now consider other phases of our combustion research, and Mr. John Sloop will conclude the discussion with a consideration of rocket problems and fundamental combustion studies.

ROCKET RESEARCH

The rocket engine is power in concentrated form. While other engines use air, which is 80 percent inert, rocket engines use fuels and oxidants that are 100 percent chemically active. It is thus easy to understand why the rocket is the most compact and powerful of all types of engines now available.

On the upper left side of ~~figure~~ the display board (see photograph C-22343, next page) is a section of a laboratory rocket engine using liquid propellants. The fuel and oxidant are injected, mixed and burned in the combustion chamber, and the hot gases are expanded through the nozzle to produce forward thrust. This is a very small rocket engine yet using high-performance propellants it could propell a 200 pound missile to a speed of 5000 miles per hour and develop over 10,000 horsepower.

Figure 30 illustrates the importance of high-performance fuels and oxidants. Shown on the bottom scale is pounds thrust developed for every pound of fuel and oxidant consumed per second; this is called specific impulse and it is an important factor in comparing rocket propellants. Rocket's in use at the present time have a specific impulse less than about 225. For example, the V2 which uses liquid oxygen and alcohol as propellants, has a specific impulse of about 200. The vertical scale is relative flight range; that is, relative to the range of the V2 which is taken as unity. We see that a fuel-oxidant combination giving a specific impulse of 340-about 1-1/2 times the specific impulse of the V2- could triple the range of the V2. NACA propellant research is concentrated in high-performance region. Fuel and oxidant combinations shown by theoretical calculations and other considerations to be of potential advantage are being experimentally evaluated in rocket engines. Experimental results already obtained at the laboratory, if applied to a rocket missile similar to the V2, could more than double the range of the V2. Other combinations are being evaluated that will give much higher ranges.

Concurrent with the propellant research, the laboratory is studying the mixing and combustion processes in a rocket engine. For the rocket engine previously mentioned about three quarts of liquids are injected every second and during that second they must mix thoroughly, burn and be expelled. One line of attack on this problem has been high-speed photography of rocket combustion. The center rocket shown ~~by figure~~ on the display board is a transparent rocket engine used for such work. The plastic walls erode only slightly during the few seconds needed to obtain the photographs. By this technique several methods of propellant injection have been studied by motion pictures taken at a rate of 3000 frames per second and recently some motion pictures were obtained at a rate of 40,000 frames per second.

Combustion temperatures in high-performance rocket engines are very high, over 5000° F- and ordinary methods of cooling are not good enough. A promising method of cooling under investigation by the laboratory is internal film cooling where a layer of coolant is maintained on the inner surfaces of the engine and in direct contact with the hot gases. Experimental results obtained by the laboratory show this method of cooling to be very effective, provided a proper distribution of the coolant is obtained. The third rocket engine ~~shown by figure~~ on the display board shows one method of introducing the coolant. The coolant is brought in through these hobnail injectors and spread along the inner wall. Another method of introducing the coolant that is under study is by means of porous metals. On the shelf below the display board on the left side ~~of figure~~ is a porous metal ring that is part of an experimental rocket engine. The coolant passes from the outside through the metal and forms a uniform layer on the inner surface. Several of these rings are necessary for efficient cooling of a complete rocket engine.

COMBUSTION FUNDAMENTALS

In addition to combustion research on specific powerplants such as the ram-jet, the turbo-jet, and the rocket, the NACA is conducting research on basic problems relating to combustion that, at first glance, seem far removed from immediate application. ~~Figure — shows~~ Some of the problems under active investigation are Air mixing and turbulence- that is a fundamental study to determine how two air streams mix to provide an insight into the proper mechanism of mixing dilution air with the hot combustion gases in a turbo-jet engine. Flame propagation- this is a study of gas inlet conditions, turbulence, fuels and fuel additives on the rate of flame propagation and stability. Dynamics of fuel droplets: This is a study of the factors governing insight into methods of achieving good fuel-air distribution. Reaction kinetics- this work will provide an insight into mechanism of combustion from a study of intermediate products of reaction; a mass spectrograph is being used in this study.

CONCULSION

In conclusion, it is hoped by means of these fundamental combustion studies and by systematic empirical research to evolve a rational method of combustion chamber design for jet engines.

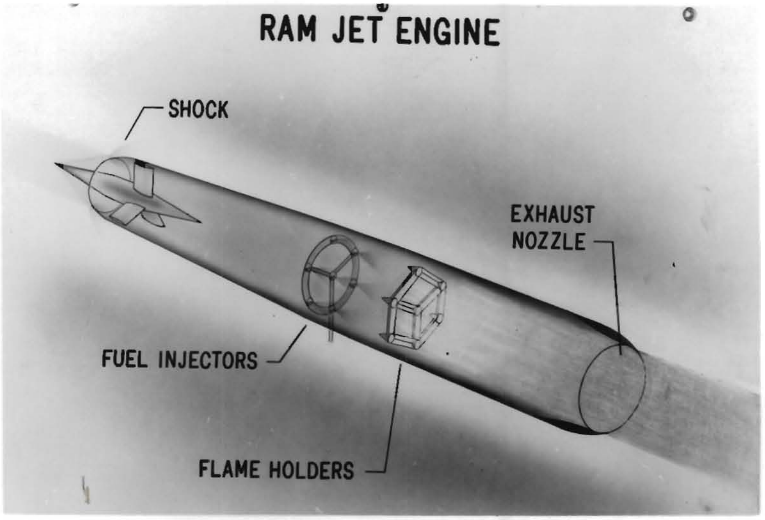
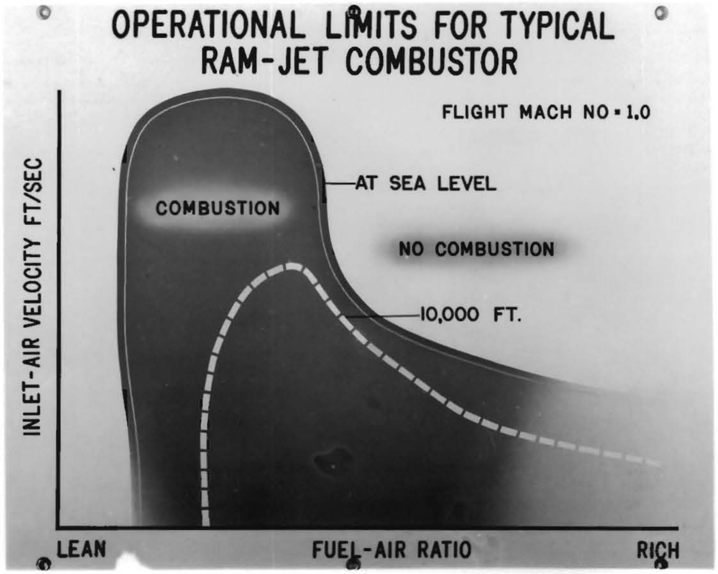


Figure 23.



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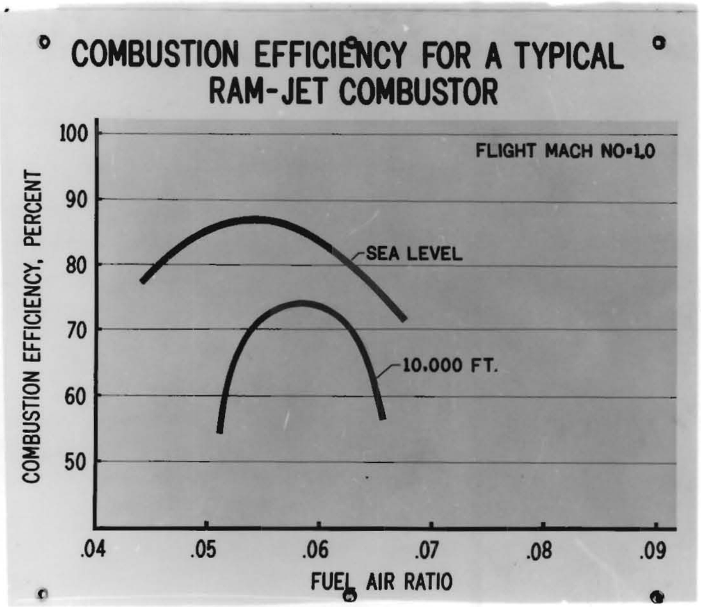

Figure 25.

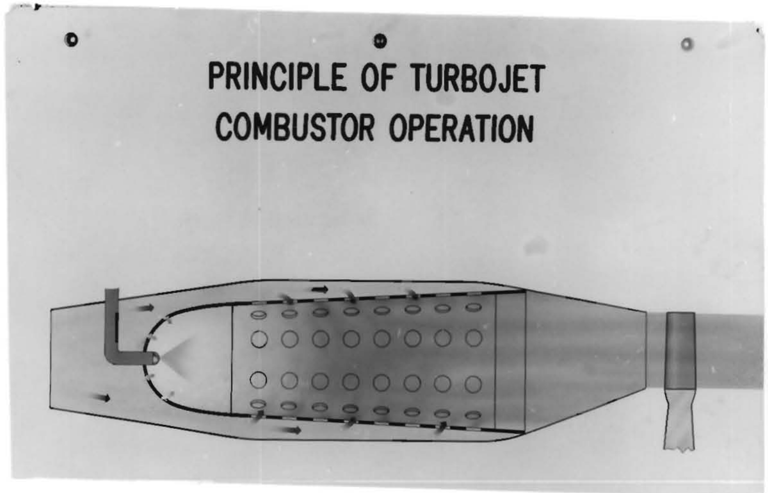

Figure 26.

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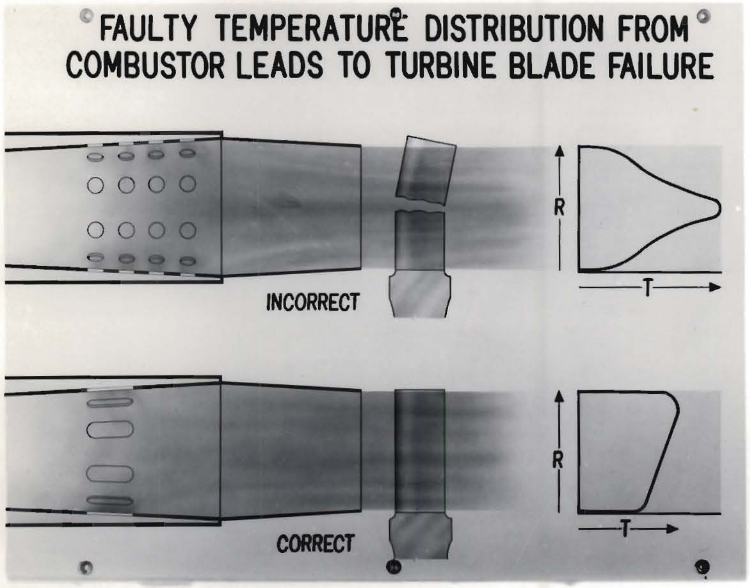

Figure 27.

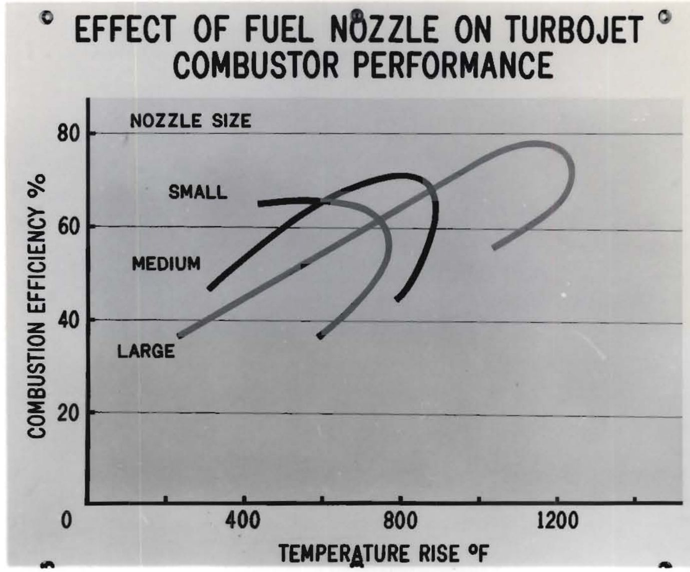

Figure 28.

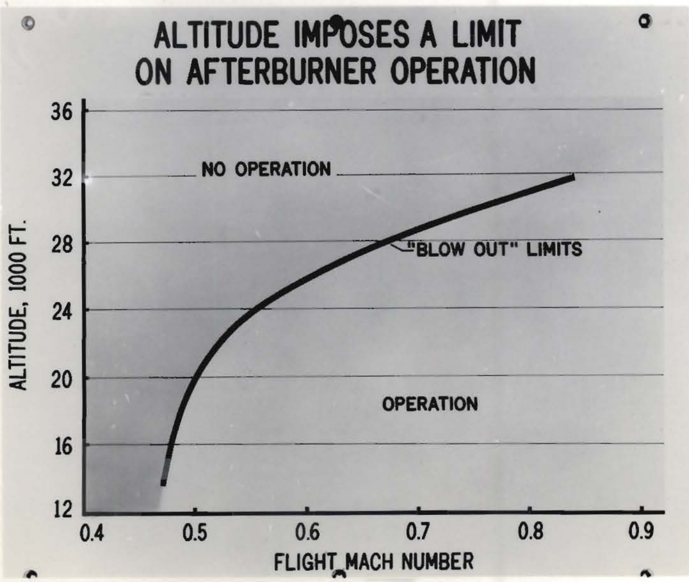

Figure 29.

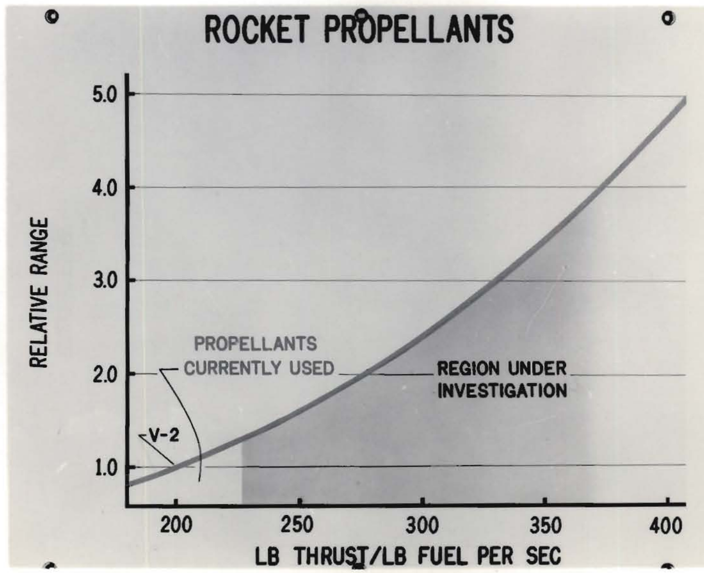

Figure 30.

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COMBUSTION RESEARCH
FEET / SECOND
IR VELOCITY
ROCKET ENGINES
RAM JET FLAME HOLDERS
RAM JET ENGINE
SCOPE OF RESEARCH
RAM JET
GAS TURBINE
ROCKET
19B COMBUSTOR ASSEMBLY
J-35 COMBUSTOR ASSEMBLY
C-22343
9-28-48

NACA

FUELS DISCUSSION FOR THE

SECOND ANNUAL MANUFACTURERS' CONFERENCE

Our research is directed toward improved performance of fuels in turbojet ram jet, rocket and reciprocating aircraft engines. The present discussion will be confined largely to the topic of turbojet and ram jet fuels. Consideration of the problems associated with the establishment of an optimum fuel for turbojet engines indicates that among the important problems those listed on figure 31 should be considered. We shall discuss each of these topics in turn: maximum availability, influence of fuels on engine performance (the three topics under this heading which we wish to discuss today are combustion efficiency, altitude limits and carbon formation). The last item for discussion is the influence of the fuel on flight range. This is by no means a complete list but is sufficient to illustrate the type of research under way here.

Going back to the first item on the list it is important that our turbojet aircraft be designed to use a fuel that is available in large quantities. Our jet aircraft today operate on a kerosene type fuel that is available in relatively small quantities. As turbojets are brought into increased use it is important that engines should be designed to utilize a fuel of greater availability than that now in use.

On figure 32 is shown the relative quantity of the present kerosene type fuel available from a barrel of crude oil -- about 5 percent. Past experience would indicate that it is desirable to use a jet fuel that will be available in much greater quantity. At the end of the last war the Armed Forces were using 600,000 barrels of aviation gasoline per day. Published figures for the production of crude oil in this country indicate more than 4,000,000 barrels per day are produced. This indicates that in case of an emergency our aviation fuel requirements would be at least 15 percent of our total production, if we used fuels only in the same quantity required previously. A large portion of this requirement probably would be for jet aircraft. Therefore, it is desirable to use a fuel for turbojet engines that is available in quantities of 25 percent or greater from a barrel of crude oil produced in the United States.

The Air Force, the Bureau of Aeronautics, and the NACA are cooperating in a program to evaluate in jet engines fuels of maximum availability. Such fuels are quite different from the present type and many factors must be investigated before new fuels can be put into general use.

One of the parameters under investigation by the NACA is combustion efficiency.

We have systematically studied the performance of a large number of fuels of different molecular structure and boiling point and our investigations show that both the boiling point of the fuel and the molecular structure have a marked effect on turbojet combustor efficiency at high altitude conditions. This helps to define the fuel types that can be used in a more plentiful jet fuel. Figure 33 shows an illustration of differences in combustion efficiency encountered with fuels of different molecular structure. The examples chosen are the well-known hydrocarbons, normal heptane and isooctane. These constitute the components of the octane scale used as a measure of the knock-limited performance of reciprocating engine fuels. Normal heptane with an arbitrary value of zero on the octane scale gives a knock-limited imep of 30 at lean mixtures in a CFR engine. If we add 20 percent isooctane the knock-limited power increases. Adding more isooctane gives increasing knock-limited power.

Following this curve we see that isooctane will give almost four times the knock-limited power of n-heptane at this particular engine operating condition. Now if we consider the combustion efficiencies of these two fuels in a jet combustor at a severe operating condition we find that the trend observed with the reciprocating engine is reversed. Considering now the lower figure we have plotted on the abscissa against composition of the fuel. At this corner we have pure n-heptane and along this scale the isooctane percentage is increased. On this scale we have plotted increased combustion efficiency, if we consider the combustion efficiency of pure isooctane as our base line. This figure indicates that as the isooctane concentration is decreased the combustion efficiency increases until the pure heptane gives a combustion efficiency about 18 percent greater than isooctane.

A second parameter under investigation by the NACA is the altitude operational limit of combustors encountered with different fuels. Here again we are systematically studying fuel components that would be used in a fuel available in quantity. One of the interesting things we have learned here at the laboratory is that if we operate in the same engine two fuels of different boiling point, differences as large as 13,000 feet in altitude operational limits were obtained. To illustrate different burning characteristics of fuels we have under this bell jar two burners containing fuels of different boiling point. We shall ignite both fuels and create a vacuum within the bell jar to correspond to altitude conditions and we shall observe that one fuel ceases to burn at a lower simulated altitude than the other. Fresh air is allowed to enter the bell jar continuously so that combustion does not cease due to lack of oxygen.

This experiment, of course, does not simulate the conditions encountered in jet engines at altitude conditions but does serve to show differences in the combustion characteristics of two fuels of different boiling point at the low air pressures encountered at high altitudes.

A third parameter that is being investigated is the tendency of fuels to deposit carbon in turbojet combustion chambers. Here again we are investigating independently both the influence of the boiling point and the molecular structure of the fuel on the carbon forming tendency. To illustrate the influence of molecular structure on this tendency figure 34 shows the structure of hexane with six carbon atoms in a chain compared with benzene that has six carbon atoms formed into a ring. The hexane forms no carbon when burned in a turbojet combustor, whereas benzene does form carbon around the fuel nozzle in the dome of the combustor and on the liner where the fuel spray impinges. Because both contain the same number of carbon atoms their boiling points are about the same but benzene forms much more carbon during combustion than n-hexane does, so the difference must be due to the molecular structure.

We have some engine parts here to show different carbon formations obtained with different fuels. A fuel with an aromatic ring similar to benzene, but higher boiling, gave this carbon formation in the combustor dome and liner. Such carbon formations tend to change the airflow pattern and the pressure drop through the combustor. Another fuel operated under the same conditions gave only a little soot in the dome and liner. This fuel contained about 20 percent of the benzene type fuel and we would anticipate no trouble in engine operation. These deposits were obtained from operating four hours at a simulated altitude of 20,000 feet.

Our investigations have shown that carbon deposition can be correlated with the boiling point and the hydrogen-carbon ratio of the fuel. Figure 35 ~~The next chart~~ illustrates how the correlation may be applied. Here at the laboratory we have determined the carbon-forming tendencies of about 50 fuels, both pure and complex mixtures.

If we determine experimentally the amount of carbon deposited by a fuel we put the data into this correlation by knowing the boiling point of the fuel, the H/C ratio and locate a point here corresponding to the carbon deposited.

If we know the boiling point of the fuel and the H/C ratio we can follow this same procedure to predict carbon formation without having to evaluate the fuel in a burner.

The third point that we wish to mention briefly is the matter of range. High speed aircraft are built with thin wings and a small fuselage. Consequently the space available for fuel tanks is very limited. Therefore it is desirable to use a fuel that will deliver the maximum amount of energy per unit volume. The burning of metals will yield more energy per unit volume than anything known except nuclear energy. For example, aluminum will deliver three times as much heat energy and boron four times as much heat energy on a volume basis as aviation gasoline.

This indicates that the use of metals instead of gasoline for a ram jet would allow a three- to four-fold reduction in fuel tank space, or maintaining the tank size the same it would allow a corresponding increased flight range for the aircraft. In addition the metals under discussion burn with a very hot flame and this allows the use of a smaller frontal area for an engine than that required for hydrocarbon fuels. The calculated thrust to be obtained in a ram jet from three fuels is shown on figure 36. The thrust for gasoline at a Mach number of 3.5 is calculated to be 3000 lb/sq ft of burner cross-sectional area. The thrust for aluminum is about 4200 pounds or an increase of 40 percent and the thrust for boron is 5200 pounds or an increase of 73 percent over gasoline. Incidentally, both aluminum and boron are present in abundance in the earth's crust. From consideration of the energy release of metals one might expect that the combustion would make a great deal of noise. Our experience has been just the opposite. Aluminum burns very quietly -- in fact much more quietly and with less pulsations than we experience with hydrocarbon flames.

We shall burn aluminum with air in a small model to demonstrate to you the quiet burning and the intense white flame experienced with metal burning.

-- aluminum burning demonstration --

Because metallic fuels give solid products of combustion it would be unlikely that they could be used in turbine engines. For such engines, however, we are conducting research on methods to utilize hydrocarbon fuels which will allow extended flight range. Here we have a jar containing aviation gasoline. See photograph C-22337, next page, left center. This volume of gasoline when burned completely will yield 225,000 Btu's of heat energy. In this next jar we have kerosene with the same number of Btu's, 225,000, but occupying 14 percent less volume. In terms of an airplane this space could be filled with fuel and the flight range could be increased over that obtained with gasoline. In this third jar we have methyl naphthalene which will deliver the same heat energy as the gasoline but in this case we have 35 percent of additional volume that when filled with fuel will allow about 35 percent greater flight range. Burning such fuels gives excessive carbon deposits and we are conducting research on suitable methods for utilizing the fuels so that extended flight range can be achieved. There are a number of hydrocarbons to be found in some petroleum stocks which give promise of extended flight range for aircraft. We wish to separate them from petroleum and systematically study them as aircraft fuels. For this purpose we have installed fractional distillation equipment. To demonstrate how a distillation column operates we have here a working model. (Extreme right in photograph C-22337) We have mixed a red liquid and a colorless liquid in this vessel. The colorless liquid boils at a lower temperature than the red liquid. The mixture is added into the middle of the column and runs down over the ceramic packing material. Vapors from this boiling liquid in the reboiler rise through the descending liquid and due to heat exchange on the surface of the packing the low boiling colorless liquid is vaporized, goes to the top where it is condensed into liquid again, and the

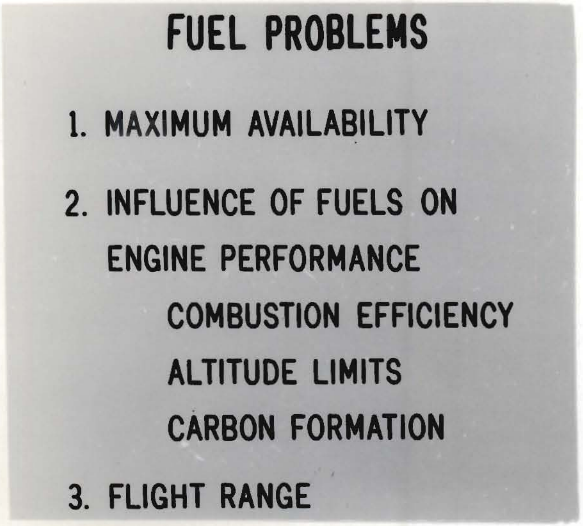

Figure 31.

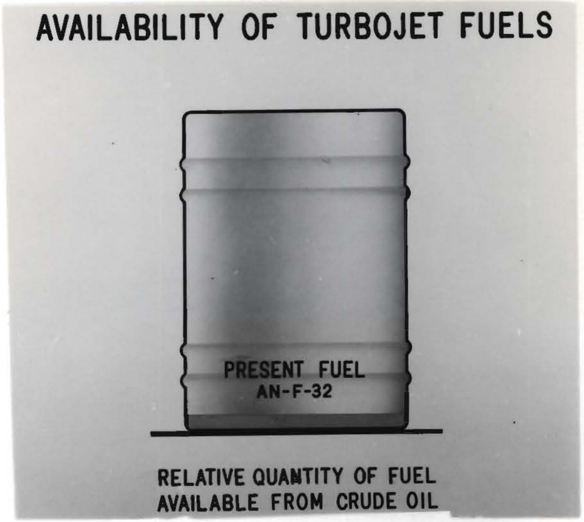

Figure 32.

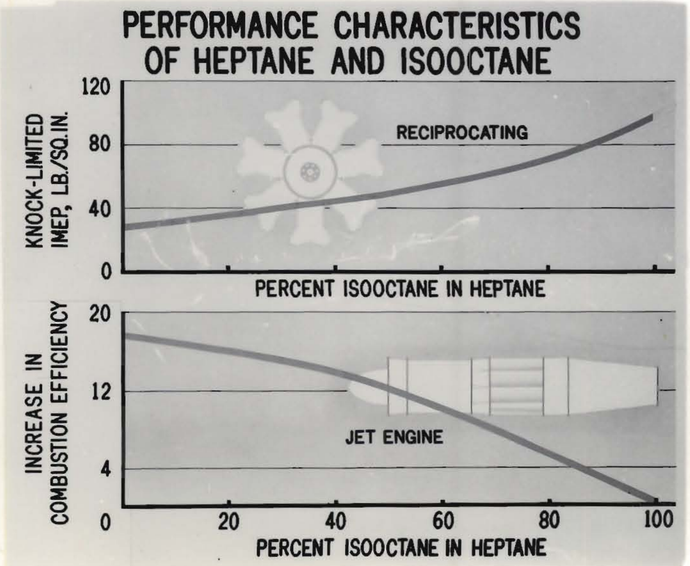

Figure 33.

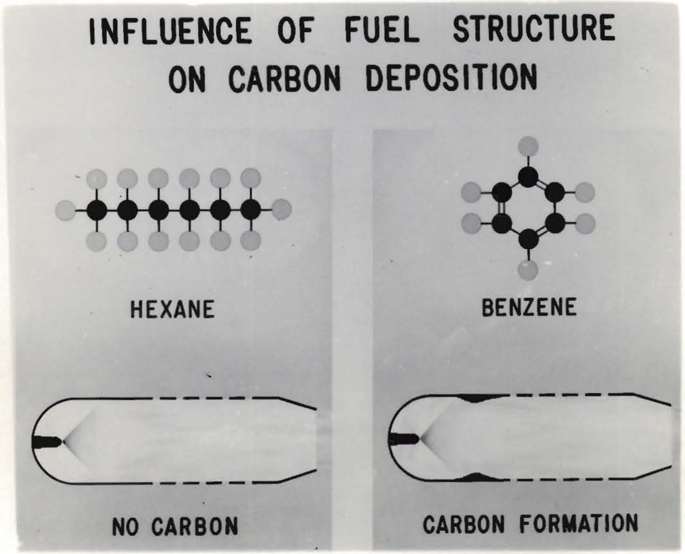

Figure 34.

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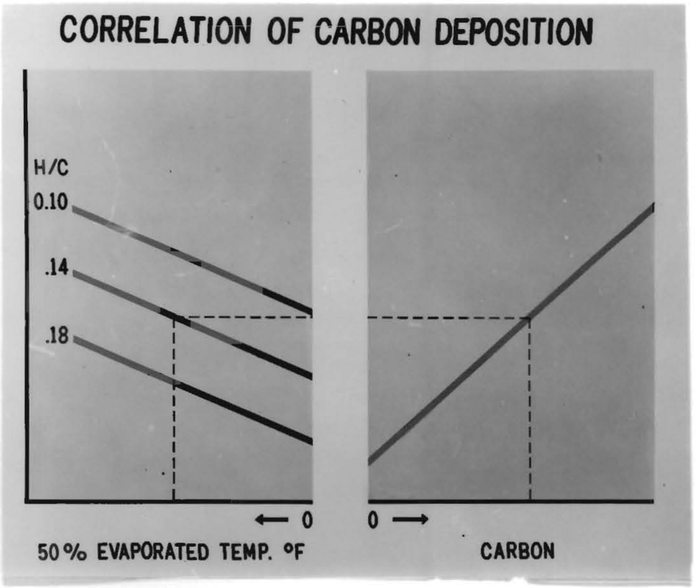

Figure 35.

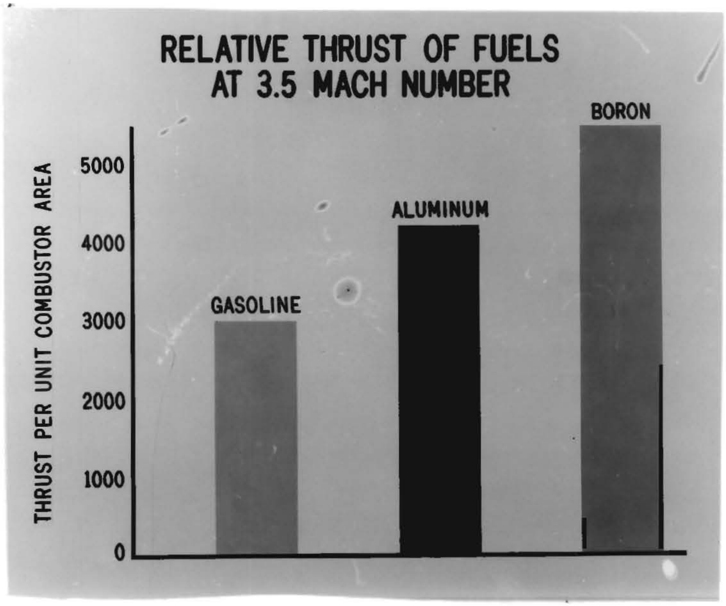

Figure 36.

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RELATIVE THRUST OF FUELS
AT 3.5 MACH NUMBER
GASOLINE
ALUMINUM
BORON
5000
2000
1000
0
HEAT ENERGY OF FUELS
GASOLINE
KEROSENE
METHYL-NAPTHALENE
ALTITUDE
50,000
30,000
10,000
FUELS
RESEARCH
C-22337
9-28-48

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