E TURBOJET ALTITUDE OPERATIONAL PROBLEMS

Stage Shot,		Color Print (Fuel Spray)	No Number
Stage Shot,		Fuel Ignition	C/24156
Chart 1	Childs	Apparatus for Fundamental Ignition Studies	C-24187-C
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1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALK ON TURBOJET OPERATIONAL PROBLEMS

Presented in the Altitude Wind Tunnel shop

by speakers as noted

(See stage photo C-24156 and color photo)

W. A. Fleming, or Dr. L. C. Gibbons:

Because future aircraft will be designed to fly at ever-increasing altitudes, an extremely important phase of turbine engine research is the continued effort directed toward increasing the effective operational altitudes of jet-powered aircraft. There are two operational problems which may limit the altitude at which a turbojet engine may be used with maximum effectiveness. The first problem is the maximum altitude to which a pilot can climb his airplane with the engine operating at constant engine speed before combustion blowout occurs, leaving the airplane ineffective. The second problem is the maximum altitude at which the pilot can expect to restart the engine and accelarate it up to operating speed. The first problem, altitude limits of engine operation at constant engine speed, was discussed at the Inspection last year. This year we will discuss the research program which deals with starting these engines during flight at high altitudes.

The problem of starting turbojet engines at very high altitudes is much more difficult than starting on the ground, or at intermediate altitudes, because the very low pressures and temperatures encountered at such altitudes have an extremely detremental effect on ignition of the fuel, combustion, and acceleration of the engine. The altitude starting problem is divided into three parts:

1. Fuel ignition.
2. Flame propagation.
3. Engine acceleration.

In starting an engine at altitude, the pilot first opens the throttle and then turns on the ignition. The location and intensity of the spark in the combustion chamber must be right to expect ignition of the surrounding fuel and air mixture. It is conventional for turbojet engines to be equipped with spark plugs in only two of the combustion chambers; therefore, after the chambers with the spark plugs are ignited, it is necessary that the fuel and air mixture be such in the other combustors and in the flame propagating tubes that the flame rapidly travels through the cross-fire tubes and ignites the other burners. After all the burners have been ignited, the pilot's problem is to accelerate the engine without encountering combustion blowout or excessive turbine temperatures. Such an acceleration requires that, as well as fly the airplane, the pilot must carefully manipulate the throttle so as not to overheat the turbine or quench the flame in the combustor. Such an acceleration at very high altitudes may require several minutes.

Investigation of altitude starting is a very complicated problem which requires getting into the heart of the engine so as to find out what is happening in the combustion chambers. Such an investigation requires a well-integrated research program between groups experimenting with ignition of ideal mixtures or ignition and combustion in single combustion chambers and groups investigating ignition, flame propagation, and acceleration in complete engine installations in altitude test chambers and the altitude wind tunnel. The research program was begun by obtaining basic data on the fundamentals of ignition of ideal mixtures of fuel and air at various altitudes. The first speaker, Mr. Childs, will demonstrate the effect of altitude on ignition of such ideal mixtures and summarize the results of this fundamental study.

I - Fundamental Studies of Fuel Ignition

J. Howard Childs, or R. Breitwieser:

The energy required for spark ignition of a combustible mixture would be expected to depend upon such factors as the pressure, the temperature, the velocity of flow past the spark electrodes and the composition of a combustible mixture. To put the design of aircraft ignition systems on a rational basis and to aid in solving the problem of starting at altitude, it was therefore necessary to have data showing the effect of these variables on the energy required for spark ignition. All of the necessary data were not available and so research on the altitude starting problem was begun by obtaining some of the necessary basic data on the energy required for ignition of flowing combustible mixtures. The apparatus used for this investigation is shown diagrammatically in the first figure (C-24182C). Air and vapor fuel from laboratory supply systems were mixed passed through a series of baffles to insure homogeneity and then passed into the test section. The test section consisted of a 2-inch diameter pyrex glass tube with spark electrodes inserted through the walls. It was possible to control the conditions of flow past the electrodes and also it was possible to control the quantity of energy supplied in the spark gap. It should be emphasized that the fuel air mixtures obtained with this type of apparatus represent ideal conditions where all of the fuel is vaporized and thoroughly mixed with the air. In the combustion chamber of an engine where much of the fuel in the vicinity of the spark plug is still in the liquid state, conditions are much less favorable for ignition. An apparatus of this type has been constructed behind the panel and the test section is visible through this observation room. Subsequently, some of the test data obtained with this type apparatus will be presented but first a demonstration will be made to show how an increase in altitude effects ignition.

The velocity of flow through this pyrex tube is about 50 feet per second and the pressure altitude inside the tube is 30,000 feet as indicated by the gage. When the spark is turned on and fuel is admitted to the test section, ignition occurs. If you watch closely you can see that the flame propagates in all directions away from the spark electrodes and consumes the combustible mixture within the tube. The flames are then blown downstream. This is because there are no shielded zones in this apparatus where the flame can burn stably as it would in the combustion chamber of an engine. The pressure altitude will now be increased and we will again attempt to obtain ignition using the same spark intensity as was used before. As indicated by the gage the pressure altitude is now 45,000 feet and when fuel is admitted to the test section, no ignition results although a combustible mixture is flowing past the spark electrodes. In order to obtain ignition at this higher altitude, the spark energy must be increased. The spark energy is now approximately three times as great as the energy previously used, and now when fuel is admitted to the test section, ignition does occur. And thus to obtain ignition at the higher altitude condition, it was necessary to utilize a larger quantity of energy in the spark.

Some of the test results obtained with this type apparatus are shown in the next figure (C-24187-B). Relative values of the energy required for ignition of the combustible mixtures are indicated along the horizontal scale and values of the pressure within the test section expressed in terms of pressure altitudes are indicated on the vertical scale. Curves are shown for flow velocities past the spark electrodes of 0, 25 and 54 feet per second. At 0 velocity the energy required to ignite at 50,000 feet is thirty five times as great as the energy required to ignite at sea level. As the flow velocity is increased from 0 to 25 to 54 feet per second the energy required for ignition increases progressively. The higher values of spark energy required for ignition at the higher altitudes and higher flow velocities as indicated by this portion of the scale are fortunately easily available by a simple re-design of many of the current aircraft ignition systems. The data in this figure were obtained using a combustible mixture having the optimum composition for easy ignition. The effect of variations in the mixture composition on the required energy for ignition is shown in the next figure (C-24187-A).

Values of the mixture composition expressed in terms of fuel air ratio are indicated on the horizontal scale. Relative values of the energy required for ignition are indicated on the vertical scale. Curves appear for flow velocities past the electrodes of 5 and 54 feet per second. These data show that the energy required for ignition is much less if the mixture composition is some where near this optimum value than if the mixture is either fuel rich or fuel lean. Increasing the flow velocity from 5 to 54 feet per second, approximately doubled the energy required for ignition. These data show the importance of so locating a spark plug within the engine that the electrodes would be in a region where the flow velocity is low and the mixture composition is some where near this optimum value.

W. A. Fleming, or Dr. L. C. Gibbons:

The results of these simple experiments indicated the increased difficulty in fuel ignition at high altitudes with ideal mixtures of fuel and air. The next step is to consider the more realistic conditions in the engine combustion chamber with which the pilot has to contend when trying to start at high altitudes. First a liquid fuel is used, instead of a gaseous fuel, and the fuel and air must be mixed in the forward part of the combustion chamber instead of being thoroughly mixed upon entering the combustion zone. This combustible mixture is obtained by a very complicated mixing process which must not only be satisfactory for ignition by the spark, but also satisfactory for the closely related phenomenon of cross firing to the other combustion chambers. Methods of obtaining a combustible mixture in the region of the spark which is also suitable for flame propagation, as well as methods for improving ignition and flame propagation, will be discussed by the next speaker, Mr. Koenig.

Robert J. Koenig or ________________:

Part II - Ignition and Flame Propagation in the Full Scale Engine.

The fuel nozzle in most common use in present-day turbojet engines is a pressure atomized hollow-cone spray type. This chart (C-24189-B) shows a cross-section of such a nozzle (chart 1). The fuel enters through these passages into a swirl chamber, where it is given a rotational velocity, and then discharges through this orifice in the form of a hollow cone which disintegrates and mixes with the air. Under desirable starting conditions we should have a fully developed spray cone which supplies fine droplets of fuel near the spark plug electrodes (C-24189-A). At altitude starting conditions, however, the fuel flow required by the engine is 1/30 of that at maximum engine power at sea level and the fuel pressure 1/900th. This low pressure will not give a good spray with a fixed area nozzle such as I have shown you and consequently ignition is difficult.

A more complex design of hollow-cone nozzle, known as a variable area nozzle, is under investigation at this laboratory. As fuel flow decreases, these passages are reduced and the pressure remains practically constant. Consequently, a good fuel spray is maintained.

To show you the types of sprays furnished by the two nozzles, we have mounted in this spray chamber (switch on light) a constant area nozzle on your right and a variable area nozzle on your left (turn on fuel flow). The fuel flow through each nozzle is the same -- that is, the flow for starting at altitude --

You observe that the spray on the right is very poor and the fuel could not be ignited with a spark plug in the normal position. (refer to chart 2) The spray on the left from the variable area nozzle has a wide angle and very fine droplets and can be readily ignited by the spark plug.

The fuel temperature in this case is at room temperature -- about 70° F (point to potentiometer). Actually, at altitude operating conditions, the fuel may be very cold (switch to cold fuel) and the spray is still poorer because at low temperatures the viscosity of the fuel is increased. I have turned a valve to circulate the fuel through a cooling bath and you may observe that the temperature is dropping rapidly as indicated on the temperature gage (point to it) and the fuel sprays are becoming progressively poorer.

Here at -40° F the spray from the fixed nozzle has turned into a dribble which would be impossible to ignite with the spark plug in the normal position, whereas the variable area nozzle gives a satisfactory spray.

This demonstration indicates that ignition at very high altitudes with a fixed area fuel nozzle would be very difficult or impossible with the spark plug located in the normal position. Therefore, research has been conducted here on methods of starting full scale engines equipped with fixed area nozzles and with variable area nozzles (point to each).

Our research results confirmed the demonstration in that we found that, with the coarse, poorly developed spray, it was impossible to get ignition at high altitudes with the normal engine configuration. However, it was learned that it was possible to ignite by moving the spark electrodes into the fuel region and providing a more intense spark than originally provided. By these changes altitude starting (limits) were raised 50%.

As Mr. Fleming mentioned, after ignition is obtained in the burners where the spark plugs are located, the flame must propagate through the cross-fire tubes to the other burners, and that brings us to the second phase of the starting process, namely, flame propagation (point to it).

It was learned that, with some engines at very high altitudes, it was possible to get ignition of one burner, but the flame would not propagate. Research on this problem indicated that larger cross-fire tubes would allow the flame to spread to all the burners at the very high altitudes at which ignition was obtained.

Thus, the maximum altitude at which ignition and flame propagation were obtained with a coarse fuel spray were increased 50%.

In addition to the research on methods of starting with a coarse fuel spray, the effect of a fine spray from the variable area nozzle (point) is also under investigation. Although results to date have been obtained only at sea level conditions, marked improvements have been obtained in ignition and flame propagation. With such a spray, ignition and flame propagation occur almost instantaneously when the spark is located in the normal position (point) and with the conventional size cross-fire tubes. This is in contrast to the results obtained with a spray from a fixed area nozzle where there is considerable delay.

We have a movie to show you the types of ignition and flame propagation that are obtained with both types of nozzles installed in a turbojet engine. First, we shall see the results with a fixed area type. This scene is taken in the control room where the operator has turned on the ignition and is now opening the fuel throttle and the main fuel valve. The temperature gage will indicate temperature rise when ignition occurs. There is a delay between the time the throttle is opened and the temperature begins to rise. During this time, fuel is accumulating in the engine. Now, the temperature is rising rapidly and the operator is pulling back on the throttle to keep from exceeding a safe operating temperature. Now it is too high -- now dropping -- now up again while the operator juggles the throttle.

To show what happened inside the engine during such a start we have now a view of the engine from the rear with the tail pipe and exhaust cone removed to permit a view through the turbine into the combustion chambers. After the spark is turned on and the throttle opened, there is a delay before the coarse fuel droplets are ignited. Now you see ignition in the two burners provided with spark plugs and now the slow, erratic flame propagation to the adjacent burners. The flame is burning through the turbine because the large drops of fuel are not burning efficiently. Finally, the flame draws back into the combustion chambers. Now I will show ignition and flame propagation with the finely atomized sprays. The operator opens the main fuel valve only and allows the throttle to remain at idel fuel flowposition. Ignition is quite rapid as you note by the temperature gage. The temperature rise indicated by the gage is slower than the actual rise due to thermocouple lag. Note that the temperature reaches and remains at the limiting value with no movement of the throttle.

This, of course, is very advantageous from the point of view of the pilot. Now we shall see the view of the engine again and the ignition is so rapid you must look closely to see it occurring. The flame quickly draws back into the combustion chambers, indicating good combustion efficiency. The movie shows conclusively that the fine spray from the variable area nozzle gives marked improvement over the coarse spray from a fived area nozzle in both ignition and flame propagation at sea level starting conditions.

We expect to extend our research to altitude starting conditions in the near future.

Mr. W. A. Fleming or Dr. Gibbons: We have seen that the maximum altitude at which the pilot can expect ignition has been raised by 50 percent over that at which consistent ignition was previously obtained, and the maximum altitude at which flame propagation can be obtained was also raised by 50 percent and is the same as that for ignition. Now the problem becomes acceleration of the engine without encountering combustion blowout or overheating the turbine. The effect of altitude on turbojet engine acceleration and the results of research devoted to raising the maximum altitude for acceleration will be discussed by the next speaker, Mr. Wilsted.

Part III - Engine Acceleration at Altitude

H. D. Wilsted or K. R. Vincent -

After ignition is obtained the next phase of the altitude starting problem is to accelerate the engine to a useful speed. This acceleration involves, however, a fundamental difficulty. The weight of the rotating parts which must be accelerated and hence the power required for acceleration are as great at altitude as at sea level. However, the air flow through the engine and hence the power available to the turbine drop rapidly as altitude is increased. For example, at 50,000 feet the turbine power is only about 1/6 of that at sea level.

In addition to this fundamental difficulty, we also have the problem of avoiding excessive turbine temperatures and combustion blow-out. Excessive turbine temperatures may result from the injection of too much fuel into the combustion chamber. Combustion blow-out is encountered when the pilot opens his throttle so rapidly as to supply a considerable excess of fuel which actually quenches the flame. To obtain an increase in engine and aircraft speed the pilot must carefully manipulate his throttle so as to avoid either of these conditions.

Altitude acceleration has been investigated at this Laboratory with a current type full-scale turbojet engine. Some of the results are shown on the next chart (C-24188-B). The acceleration in terms of percentage increase in engine speed in a given time interval is plotted against throttle advance, which is roughly proportional to the fuel supplied to the engine. Curves are shown for three different altitudes. As the throttle is advanced and the fuel supply increased there is a rapid rise in gas temperature, which produces this rise in engine speed. At this throttle advance at which maximum acceleration is obtained, maximum turbine temperatures are also encountered. These maximum temperatures may exceed the safe operating limits of the turbine. As the throttle is further advanced, excessive fuel begins to quench the flame, with resultant decrease in acceleration, until combustion blow-out is encountered in this region. The pilot is then faced with the problem of trying to restarthis engine. Now, this curve is for a low altitude; at an intermediate altitude the maximum acceleration is reduced and is obtained at a smaller throttle advance. At the high altitude no acceleration is obtained and blow-out occurs at a very small throttle advance. This effect of altitude on permissible throttle advance is very critical for the pilot. At high altitude, he must slowly manipulate his throttle to obtain acceleration and at the same time fly his plane in combat. One method of relieving the pilot of these duties is to use automatic controls; but this cannot increase the rate of acceleration of the engine even though they will avoid excessive turbine temperatures and combustion blow-out.

To return now to the fundamental aspects of the problem involved in the altitude acceleration, recall that the power required to accelerate the rotating parts remains constant while the power supplied to the turbine drops rapidly as altitude is increased. Now turbine power may be boosted by increasing the pressure drop across the turbine. In a turbojet engine this may be accomplished by lowering the pressure downstream of the turbine by enlargement of the exhaust-nozzle area. This requires use of a variable-area exhaust nozzle, so that after acceleration has been obtained the nozzle area can be reduced to that for best performance under normal operating conditions. We have here a model of one type of variable-area exhaust nozzle. It consists of two moving segments which can be opened and closed to change the nozzle-exit area.

An investigation of altitude acceleration has been conducted using a variable-area exhaust nozzle. Results are shown on the next chart (C-24188-A). The time to accelerate the engine from starting speed to full engine speed is shown for a low and a high altitude. The solid red bars show the time required to accelerate the engine to full speed with the variable-area nozzle in the closed position. This corresponds to operation with a standard fixed-area exhaust nozzle. At the higher altitude there is an appreciable increase in the time required to accelerate the engine to full speed. When an acceleration is made with the variable-area exhaust nozzle in the open position, as shown by the cross-hatched bars, the time required to accelerate to full speed at both high and low altitudes was reduced to half that required with the nozzle in the closed position. If this is considered to be the maximum time allowed to accelerate the engine at altitude, then it can be seen that with the variable-area exhaust nozzle it is possible to accelerate at a higher altitude in about the same time interval. This improvement amounts to a 30-percent increase in altitude.

Another method of improving altitude acceleration is to decrease the weight and therefore the inertia of the rotating parts, thereby reducing the turbine power required for acceleration. Methods of reducing the weight of the moving parts of a turbojet engine are being discussed at another demonstration.

Research directed towards further improvement of engine acceleration at altitude is being continued at this Laboratory by investigation of the three fundamental problems affecting acceleration.

1. Improvement in stability and control of combustion.
2. Increase in turbine power.
3. Reduction of weight and inertia of the rotating parts.

W. A. Fleming or Dr. Gibbons: We have seen that inserting the spark plug further into the combustor and using a larger spark gap and higher spark energy, doubling the cross-section area of the cross-firing tubes, and installing a variable-area exhaust nozzle has raised the maximum altitude at which the pilot can ignite the fuel, expect all the burners to be quickly ignited, and accelerate the engine. This altitude at which starts can be made is nearly as high as that limiting operation of the engine at constant engine speed which was mentioned earlier. These altitude operational limits of starting and constant-speed operation are adequate for current turbojet aircraft; however, research is being continued to further extend these altitude operating limits to meet the requirements of future aircraft.