FUELS AND COMBUSTION RESEARCH

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In the course of your inspection of the laboratory today, you will see demonstrations of the various engine components in modern jet aircraft. In this discussion we will demonstrate some of the important elements in the combustion process which supplies the propulsion energy. We will show you typical experiments used to gain a better understanding of the fundamental factors in combustion processes. This information aids the engine manufacturer to properly design the combustion chamber. Such studies include the selection of fuels for various types of aircraft; and the equipment you see around you is used to prepare pilot plant quantities of pure fuels for our fuels and combustion research.

The combustion process consists of three basic steps listed on the backdrop:

1. Combustible mixture preparation
2. Ignition
3. Flame propagation

Combustible mixture preparation is the process of vaporizing and mixing the fuel with air, the same job performed by the carburetor in your automobile.

This mixture must be ignited by means of a spark or other ignition source and finally, the flame must propagate into the remainder of the mixture so that flame propagation refers to the actual burning of the combustible mixture.

To illustrate these basic processes, experiments on the burning rate of different fuels, flame volume, ignition energy, flame speed and spray formation will be demonstrated. These processes exist in any type of combustion engine, only the physical conditions under which they occur changing from engine to engine. Let us consider some of these steps in terms of three current types of propulsion system -- the rocket, turbojet, and ram jet.

First let us consider the turbojet. Here the air is supplied to the combustion chamber from a mechanical compressor, enters through the holes in the side of the chamber where it mixes with the fuel spray. Ignition is accomplished by means of a spark, the flame rapidly spreading to the remainder of the chamber. Considering average conditions, only 1/100 to 2/100 of a second are available for the three essential combustion steps -- mixing of fuel and air, ignition, and burning.

The next engine -- the ram jet -- is similar to the turbojet except that air is compressed by the ram action of the moving missile rather than by mechanical compression.

In the ram jet, the fuel-air mixture is again prepared by spraying fuel into a moving air stream. Ignition may be accomplished by means of a spark or a small pilot flame as shown here. Burning occurs from a sheltered region called the flame holder and spreads rapidly into the combustible mixture flowing around it. Since the ram jet is designed for even higher speeds than the turbojet and since the cross-sectional area must be kept small to reduce drag, these processes of combustible mixture preparation, ignition, and flame propagation must occur in less than 0.005 second.

In the two engines just described the fuel is oxidized by the oxygen in the air. In the third combustor -- the rocket -- the basic processes are the same but the oxidant can consist of many different types of chemical oxidizers such as liquid oxygen, nitric acid, or liquid fluorine. Here the fuel and oxidant enter as impinging jets, mixing being accomplished by the heat and turbulence produced in the interacting jets. The ignition energy is often supplied by the initial reaction of fuel and oxidant -- so called spontaneous ignition. This is similar to the spontaneous reaction that occurs in a pile of oily rags but in a rocket ignition must occur in milliseconds. A thousandth of a second for spontaneous ignition, not several days. The flame reactions once initiated occur at high pressure within the rocket chamber.

We have now seen where the three basic processes occur in the various engines. Note again the extremely short time available -- from 1/100 second to 1/1000 second for a sequence of three steps. Now when the manufacturer sets out to design an engine he can determine the maximum rate for each of these steps from fundamental experiments in idealized systems. He must compromise this information with the factors of engine weight, cost, and complexity of manufacture to design the actual component, the combustor. Once the component has been developed, it must be coupled with the remainder of the engine to get optimum over-all performance.

Today we will demonstrate some of the basic experiments which supply the designer with the necessary conditions.

Let us first consider the process of combustible mixture preparation.

(The talk is continued by Demonstrator I)

As mentioned previously, the fuel-oxidant preparation consists primarily of fuel evaporation, followed by turbulent mixing of fuel and oxidant. In the turbojet and ram jet this is accomplished by spraying liquid fuel into the moving air stream. The rate of mixture preparation, then, will depend upon both the fuel properties and the air flow conditions.

To study the effectiveness of the fuel-spray interaction with the air entering the combustor, high-speed motion pictures are taken in transparent combustor models. Note the inlet

air ports, and the location of the fuel spray nozzle and of the ignition electrodes. In the motion picture to follow, you will see high-speed photographs of fuel sprays under simulated operating conditions.

MOVIE -- about 1½ minutes

Part 1 - spray in still air

Part 2 - spray in moving air, inside transparent combustor

Part 3 - color movies of ignition and burning

Such pictures give us an insight into the flow patterns within a combustor, and enable the engineer to locate properly the points of fuel and air admission. Photographs such as these tell the designer what changes are necessary, and whether or not new designs have improved the process of fuel-oxidant preparation.

In the rocket, the fuel-oxidant mixture is often made by impinging jets of two liquid streams. A typical arrangement is shown in the rocket model and has been assembled in this box. (Start water jets.) Note the apparently smooth spray that forms. A smooth and steady flow of fuel and oxidant is, of course, desirable to insure smooth combustion. Actually, the simple spray you see here is deceptive, for if we illuminate is stroboscopically -- (turn out steady light, start strobe light) -- we see alternating rings of high and low spray density. Such a discontinuous spray, having an alternating frequency of

1000 to 4000 cycles per second, may be related to the rough combustion often observed in actual rockets. Alternate surges of high and low thrust result, which lead to serious mechanical stresses, as well as a loss in the over-all efficiency and control of the combustion process.

(Talk is resumed by the first speaker, the chairman.)

These demonstrations illustrate some of the types of research used to understand and improve the manner in which the fuel and air are brought together to form the combustible mixture necessary for burning. These experiments showed the mechanics of the preparation of a combustible mixture. This process can also be improved by working with the fuel properties. For example, a part of the problem requires evaporation of the fuel. By using fuels of high volatility -- fuels which evaporate rapidly -- this process can be speeded up. Let us now consider an experiment where we feed liquid fuel into a porous sphere and allow the fuel to burn off the surface.

(Talk is continued by Demonstrator II)

We have mounted here two porous spheres through which we will pass liquid fuel. We have a common liquid feed system so that both fuels will be injected at the same rate. We will now start the flow and ignite the fuel. (Ignite hexane.) The fuel now being ignited is cetane, which is difficult to ignite (ignite cetane). Now we will increase the fuel flow rate on both spheres, still keeping equal rates between the two.

Note that now the more volatile fuel,hexane, burns completely on the sphere but the less volatile fuel, cetane, burns more slowly and actually drops fall off before combustion is complete. In such a case the more volatile fuel would have a high combustion efficiency in the combustor, while the other fuel would burn only partially in the same time interval, and complete combustion would not be realized.

While the highly volatile fuels do burn efficiently, the large quantities of fuel required by jet engines makes it necessary to use the low volatility fuels also. At the present time, research is being conducted at this laboratory to find methods of using the low volatile fuels without any sacrifice of combustion efficiency.

(Talk resumed by chairman.)

These experiments have illustrated typical research techniques for studying the process of preparation of the combustible mixture. The next step in the combustion process is the ignition of the mixture. Two important conditions must be achieved -- first the previous process of preparation of the combustible mixture must place a mixture capable of burning in the region of the igniter. If pure fuel or pure air are around the igniter, obviously it cannot start a flame. Actually the proportion of fuel and air must be controlled within quite narrow limits before stable flame is obtained. The importance of proper fuel and air concentrations is illustrated in the next experiment.

(Talk continued by Demonstrator I.)

Each of these vertical glass tubes contains a mixture of a gaseous hydrocarbon fuel with air. The amount of fuel in the mixture increases as we go from left to right, in about the proportions shown by the level of the red liquid in the indicators. We will pass a spark through each of the mixtures to see if ignition will occur, and if it does, we will observe the travel of the flame from the lower to the upper end of the tubes.

Tube 1 -- the first tube, on the left, contains a very lean mixture, that is, there is very little fuel present. In fact, this first mixture contains so little fuel that it will not burn. Thus we may pass a spark repeatedly through the mixture, and no ignition will take place. In terms of a combustor, this would mean that if such a mixture surrounded the ignition electrodes, the engine could not be started.

Tube 2 -- In the second tube, we have added a little more fuel. Now when the spark is passed, the mixture will ignite and a rapid blue flame will travel from the ignition electrodes to the upper end of the tube. The mixture was easily ignited and the flame was vigorous. Such a mixture would be very desirable in a combustor. Flame would spread easily from the spark plug to the surrounding fuel-air mixture. Furthermore, many of our present turbojet engines have several can-type combustors such as this (point to model) connected by tubes, but there are spark plugs in only two of the combustors. Hence, when the engine is started,

flame must travel from the combustor fitted with spark plugs through these tubes to the adjacent combustors, and a mixture like the one we have just ignited would do a fine job of spreading the flame.

Tube 3 -- In the third tube, we have added still more fuel, and we now have a mixture that burns in an unstable manner. The mixture will be sparked and you will observe an unsteady green flame that may or may not travel the length of the glass tube. The flame did actually fail to travel the full distance. If a mixture such as this surrounded the ignition electrodes of a combustor, flame might fail to spread from the spark plug to the rest of the fuel-air mixture in the combustion chamber, and almost certainly would fail to travel through the connecting tubes to other chambers. The result would be uncertain ignition -- the engine would start occasionally, most of the time it would not.

Tube 4 -- In the fourth tube, we have a mixture still richer in fuel. The mixture will ignite, but the flame will be small, weak, and very slow. Here again, it is easy to understand how such a flame could be extinguished before it traveled very far from the ignition electrodes of a combustor and before it ignited the adjoining combustors.

Tube 5 -- Finallywe have a mixture containing so large a proportion of fuel that ignition is smothered. Just as in the case of the first tube, sparks may be passed repeatedly through the mixture and no ignition will occur. Obviously

such a fuel-air mixture would fail completely in starting and supporting combustion in an engine.

These demonstrations point out the fact that the ratio of fuel to air must be quite closely controlled or the engine can neither be started nor operated efficiently.

(Talk continued by chairman.)

Now we have said two conditions were necessary to start a fire. We have demonstrated the need for the proper proportion of fuel and air. We must also add sufficient energy in the spark to ignite the mixture. Too little energy in the spark will not cause ignition. We must add a certain minimum amount of energy -- or more -- before ignition will occur. Once we have added this proper amount of energy a stable flame begins. This is something like a mouse trap in which the bait corresponds to the combustible mixture. The mouse just nibbling at the bait corresponds to too little energy -- not enough to set off the trap. Only if the mouse puts sufficient energy into the trap does it spring shut. In the case of a combustible mixture sufficient spark energy starts a flame; in the case of a mouse trap, all we get is a dead mouse.

Well, we've seen it happen with a mousetrap, now let us see the actual experiment with a fuel-air mixture.

(Talk continued by Demonstrator II.)

In this bomb we have a fuel-air mixture capable of burning, once ignited. Identical spark plugs such as are used in jet engines are mounted in series inside the bomb

and on the panel so that you will be better able to compare the energy supplied to the mixture in the bomb. Now let us pass a weak spark. (Pass several sparks.) We can pass as many sparks as we wish, but it still is not enough to start a flame.

Now let us increase the energy of the spark. Watch closely. In this case the energy was sufficient to ignite the mixture and the flame spread rapidly throughout the bomb.

It is from experiments such as these that we are able to find the minimum amount of energy required to ignite combustible mixtures under favorable conditions. The engine designer, however, would want an energy supply that would ignite mixtures under all conditions of temperature, pressure, and fuel concentration. Thus, he must make a compromise between these two extremes, taking into consideration such additional factors as cost and weight limitations.

(Talk resumed by chairman.)

Once ignition has been accomplished, the flame must be capable of travelling indefinitely. To illustrate that a flame will propagate indefinitely, or almost indefinitely, unless disturbed, let us ignite the fuel-air mixture in the plastic tube fastened to the backdrop. (Ignite.) Watch the flame as it travels smoothly and uniformly on and on and on...

But it is not sufficient that the flame merely continued burning. We have already indicated that the time for combustion is limited so that the flame must burn rapidly. The rapidity with which a flame travels is called its flame speed. This speed is a function of the fuel type and is measured experimentally to determine the relative burning rates of different fuels.

A typical flame speed experiment will now be demonstrated.

(Demonstrator I)

We have here a typical apparatus used for measuring flame speed. These tubes contain mixtures of two gaseous hydrocarbon fuels with air. Above the tubes are two photocells which will detect the flame travel. The flame will be ignited and will travel from right to left. As it passes the first photocell, this electronic counter will start, and as it passes the second photocell, the counter will be stopped by the pulse from the photocell. The time required for the flame to pass from the first to the second cell will be recorded on the counter by a series of lights, representing tenths and hundredths of seconds. From this information we may compute the flame speed, and we will record it on this data sheet.

First we will ignite a flame in this tube, which contains a mixture of propane and air. (Ignite, read counter, record time and flame speed.)

Now we will pute the second tube in place. This tube contains a mixture of ethylene and air. (Ignite, read counter, record time and flame speed.)

We note that the flame travelled through the ethylene-air mixture almost twice as rapidly as through the propane-air mixture. Now what does this mean in terms of an aircraft engine? It means that, in a given length of time, we are able to produce almost twice as much energy, and therefore thrust, from ethylene as from propane. Although we do not use these two gaseous fuels in actual engines, differences in the flame speeds of liquid fuels show up in the same manner.

(Chairman)

The flame which you saw in the flame speed experiment had a smooth curved surface, while the flame you saw in the combustor in the motion picture had a rough, turbulent appearance. If we imagine that the smooth flame corresponds to a thin sheet of paper, then the turbulent flame would correspond to the same piece of paper crumbled into a small ball. Obviously the turbulent flame occupies less space. We can fold the flame into a small volume by introducing turbulence because, like the thin piece of paper, the flame is very thin. As we go up in altitude, however, the flame expands and would correspond more closely to a thick piece of cardboard. Obviously this cannot be compressed into as small a volume. Thus as the combustor operates at higher and higher altitudes, more space is required by the

flame. The expansion of a flame at reduced pressure is illustrated in the next experiment.

(Demonstrator II)

We can show this effect with the small burner located in this tube. We will light a flame and slowly lower the pressure in the tube. The red liquid will indicate the altitude that corresponds to the pressure inside the flame chamber. The photographs that you will see are of flames that correspond to those in the tube at specific altitudes. (Ignite the flame.)

We are at sea level now (picture 1). Note the yellow appearance of the flame, as well as the diameter of the flame at this point. The yellow color is due to incandescent carbon particles that are a result of incomplete combustion. In a jet engine, this would result in serious carbon deposition.

We are now increasing the altitude and thereby decreasing the pressure in the chamber (picture 2). At 48,000 feet the yellow has decreased considerably, thereby eliminating the carbon formation problem. We can now see more clearly the bright blue combustion zone. This bright blue outer mantle is the actual burning zone of the flame. The inside portion is utilized as a mixing chamber for the fuel and air. As we decrease the pressure, the distance between the molecules is increased, thereby increasing the mixing volume required by the flame before suitable burning conditions are obtained.

Note also that the flame diameter has increased.

We will now go still higher and see what changes take place in the flame (picture 3). We see that now the yellow has almost completely vanished. Both the flame diameter and the combustion zone thickness have increased markedly.

As we progress still higher the flame continues to expand (picture 4). Now the yellow has disappeared completely and the flame has grown even larger.

Finally as we near the blow-off limit, the flame expands rapidly and becomes unstable (picture 5) until it goes out at 85,000 feet. This would corresponds to an altitude ceiling. To show again how the flame changes with altitude, let us look at all five photographs. Three things are evident at a glance.

First, that the yellow color, predominant at sea level, disappears as the altitude increases. Secondly, we can see that the actual combustion zone thickness increases noticeably in going from sea level to the altitude ceiling of 85,000 feet. Third, it is also apparent that the flame volume increases markedly as the altitude increases.

(Chairman)

The experiments you have seen today illustrate the study of basic combustion processes. Such experiments, coupled with the research on combustors and full-scale engines, meet the goals of increasing the flight range,

speed, altitude, and economy of operation of jet-propelled aircraft. It is such combined research efforts that have resulted in engines with power almost unbelievable a few years ago and which will result in engines of even greater power in the time that lies ahead.

Setup -- Fuels and Combustion Demonstration

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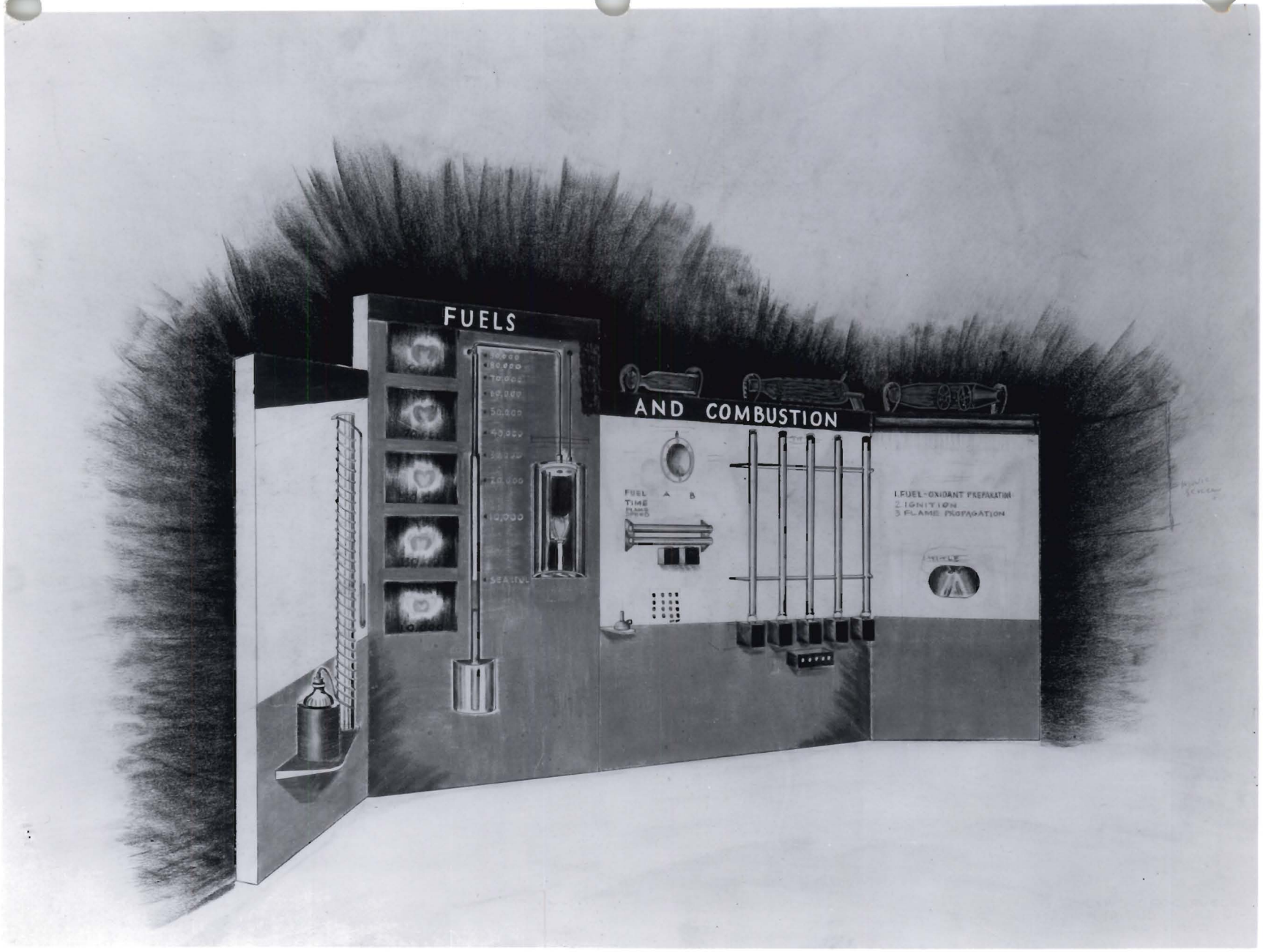
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FUEL
TIME
A
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1. FUEL-OXIDANT PREPARATION
2. IGNITION
3. FLAME PROPAGATION

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