Outline of
Proposed Talk on Fuels to be Presented
at Manufacturers' Conference October 8 and 9, 1947
by L. C. Gibbons

Introduction

No matter what type of propulsive device may be chosen as an aircraft power plant, we must have a source of energy to supply the necessary power and that source of energy, of course, is the fuel. At the present time our chief fuels research emphasis is directed toward the study of fuels for turbojets, ram jets, and rockets. Since the rocket work is the subject of another discussion, we shall confine our remarks here to the subject of fuels for turbojets and ram jets.

One of the chief sources of energy available to us is petroleum and, consequently, various petroleum fractions are being studied as jet fuels. Extensive investigations by many workers have indicated that there are hundreds, and possibly thousands, of individual chemical compounds in any sample of crude oil. Most of these compounds are composed of carbon and hydrogen arranged in many different combinations.

(At this point show molecular models of basic types of hydrocarbons. Show how as the molecular weight is increased, the boiling point is increased and other physical properties change.)

One phase of our fuels research is to determine if hydrocarbons of different boiling point and chemical structure will give differences in performance when burned in turbojet and ram jet combustors. We have compared various fuels on the basis of several parameters, some of which have been listed here -

Chart listing

Altitude Operational Limit
Combustion Efficiency
Flame Speed
Ease of Ignition
Energy per Unit Volume

Fig. 43

First let us discuss combustion efficiency. We have tested a large number of hydrocarbon fuels in various combustors of present design and in general it may be stated that at sea-level conditions of operation all of the fuels gave good combustion efficiencies. However, since aircraft normally operate at altitude it is necessary to know how various fuels will behave under altitude conditions. The next figure Fig. 44 shows the trends we have found. Here is shown a plot of combustion efficiency against altitude for two fuels, gasoline and Diesel oil. It is shown that both fuels give good combustion efficiencies up to about 20,000 feet. Then the combustion efficiency drops rapidly for both the gasoline, shown by the red line, and the Diesel oil, shown as the blue line. If we wish to go to the maximum possible altitude the Diesel oil line will cross that for the gasoline and at a very high altitude the combustion efficiency of the Diesel oil will be greater than the combustion efficiency of the gasoline. This will be discussed in more detail under altitude operational limits. But first to elaborate a bit more on combustion efficiency. If we choose a point here at an altitude of 40,000 feet where good combustion efficiency is difficult to attain and compare the combustion efficiencies of a series of fuels we get a trend shown on this figure. Fig. 45 Here we plot the combustion efficiency of the fuel against the boiling point of the fuel and find that as the boiling point of the fuel is increased that the combustion efficiency decreases. At this condition gasoline gave a combustion efficiency of about 85 percent, kerosene would be about here on the figure with a combustion efficiency of about 75 percent. and Diesel oil at the bottom with a combustion efficiency of about 60 percent.

Now to discuss briefly the part the fuel plays in the establishment of the altitude operational limit of a particular engine-fuel combination. The altitude operational limit has been discussed in a previous talk but to review briefly, the altitude operational limit of an engine is defined as that altitude where the combustion process will not give enough heat to operate the turbine. In order to partially determine the part the fuel plays in establishing this limit we have compared the altitude operational limits of gasoline and kerosene on combustors from four different turbojet engines. The next chart Fig. 46 shows the type of result obtained. This is a bar graph showing the altitude limit obtained with gasoline and with kerosene on the four different combustors. In every case the kerosene, the higher boiling fuel, gave the higher altitude operational limit. The differences varied from 2 to 8000 feet.

We might summarize by stating that in the standard combustors we have examined, gasoline will give a better combustion efficiency than kerosene up to a high altitude condition where the situation is reversed and the kerosene will continue to give sufficient temperature rise to operate the turbine but the gasoline will not.

It should be mentioned at this point that we have known for a long time that when we change the design of a reciprocating engine we may change the relative performance of fuels in that engine. We believe that if we change the turbojet combustor design or the method of introducing fuel into the engine we may change the relative performance of fuels in turbojet engines. That is a point which remains to be more fully explored as we continue our research in this field.

The third property which we wish to discuss is flame speed. For certain types of jet combustors it is desirable to have fuels which will burn very rapidly and allow short combustion chambers. Therefore we have started the systematic examination of various types of fuels in order to determine what differences in flame speed might be expected. One method for the measurement of flame speed is to introduce a combustible mixture into a horizontal tube, fire the mixture from one end and measure the rate of flame travel along the tube. In order to demonstrate differences in the flame speed of two compounds we have a combustible mixture of propylene oxide in the top tube and acetone in the bottom tube. The propylene oxide has a flame speed of one foot per second and the acetone has a flame speed of 66 cm/sec. We shall ignite the mixtures simultaneously and you will observe that the propylene oxide reaches the end of the tube when the acetone has proceeded only this far. The molecular structures of these two compounds are quite similar. This is the structure of acetone. It has three carbon atoms with hydrogen atoms attached to the end carbon atoms and an oxygen attached to the center carbon atom.

The propylene oxide has three carbon atoms also and has one oxygen atom. The only difference is that the oxygen atom is attached to two carbon atoms instead of one. This compound has a flame speed of 108 cm/sec and this has a flame speed of 66 cm/sec. As our research continues we hope to be able to understand <u>why</u> these small differences in molecular structure influence flame speed so markedly. As one step in trying to understand the influence of molecular structure on flame speed we have compared some acetylenic hydrocarbons with some paraffinic hydrocarbons. Acetylene itself has two carbon atoms with a triple bond between the carbon atoms whereas ethane, the corresponding paraffinic compound, has two carbon atoms with one bond between the carbons and the other bonds attached to hydrogen. This chart Fig. 47 shows how the triple bond will influence flame speed. Here we plot flame speed against the number of carbon atoms in the molecule. For acetylene itself with two carbon atoms we get an extremely high flame speed whereas the ethane is low. Now if we remove an hydrogen atom from the acetylene and replace it with a carbon atom and its required hydrogens the flame speed decreases markedly. Then if we add another carbon atom we decrease the flame speed again. If we continue to add carbon atoms we continue to decrease the flame speed but at a decreasing rate. By adding carbon atoms to the ethane molecule we find no appreciable change in flame speed and even with molecules of six carbon atoms the presence of one triple bond in the molecule makes the flame speed about 10 percent faster than the molecule with a single bond. This type of study is being continued with other types of fuels.

The last item I wish to discuss is the matter of energy per unit volume which may be derived from a fuel. As you know, aircraft designed for high speeds have thin wings and a small fuselage and the space available for fuel storage is extremely small. Therefore fuels are needed which will deliver the maximum heat energy per unit volume. We are conducting research on various types of fuels which will give more energy release than gasoline. This chart Fig.48 illustrates the relative energy releases of some hydrocarbons and metals. First is aviation gasoline which will release 840,000 Btu/cu ft. Then we have ethylnaphthalene which delivers 1,200,000 Btu/cu ft. This offers a gain of about 40 percent over gasoline. At the present this figure represents about the best energy release to be obtained from hydrocarbons. We are preparing new hydrocarbons which may extend this range and we are also engaged in the study of methods of burning such materials efficiently so this potential energy release will be realized in extended range. Next is graphite which will give almost two million Btu/cu ft. Then aluminum with 2,250,000 and boron with 3,340,000 Btu/cu ft. These are actual heats of combustion for solid blocks of metal. Whether these energies can be utilized in aircraft propulsion remains a problem. However, this seems to be the direction we must go if we wish to obtain heat releases much greater than about this figure of 1,200,000.

Two problems immediately come to mind when metals are mentioned as fuels. One problem is the fact that the products of combustion with air are metal oxides which are abrasive solids. The question as to what happens to such products in the combustion process of a ram jet is being actively studied at the present time.

A second problem to be considered as to the possible use of a metal is how can one successfully burn a metal in an aircraft power plant. One possible answer is that some metals form compounds with hydrogen and these materials, called hydrides, in some cases are liquids. One such liquid is aluminum borohydride which on the energy chart falls between aluminum and boron. The material is spontaneously inflammable in air and therefore would present quite a handling problem in ordinary fuel systems. However the spontaneous ignitability might prove to be a very useful property for certain applications because no ignition system would be required. To illustrate the inflammability characteristics of aluminum borohydride we have here a 1/2 gram sample sealed into a vial. The quantity of liquid is practically invisible. There is a similar vial here inside this box which we shall break with a hammer and you will see aluminum borohydride ignite.

The nature of the explosion of only a tiny quantity of the material indicates the nature of the energy released when it burns.

We believe that some of the metallic fuels offer the maximum energy release which can be obtained without utilizing nuclear energies. However, if nuclear energy can be utilized for aircraft propulsion then the heats of combustion of any material looks extremely small. The next chart Fig. 49 gives some comparative energy releases including nuclear fission. Here again we have gasoline with a heat of combustion of 840,000 Btu/cu ft. Then the best hydrocarbons we know of which give 40 percent more energy than gasoline. Then boron releases about four times more than gasoline and finally uranium fission, the reaction utilized in the atomic bomb, which will release about 50 million times more energy than gasoline. Obviously if such energies can be utilized for aircraft propulsion then our fuel storage space problems should be eliminated.

Now in summary we might state that when we test hydrocarbon fuels at altitude conditions on turbojet combustors ~~that~~ the higher boiling fuels tend to give lower combustion efficiencies but will allow higher altitude operational limits than lower boiling fuels. We are conducting research on hydrocarbons and metal fuels which we hope will extend the range of volume limited aircraft.

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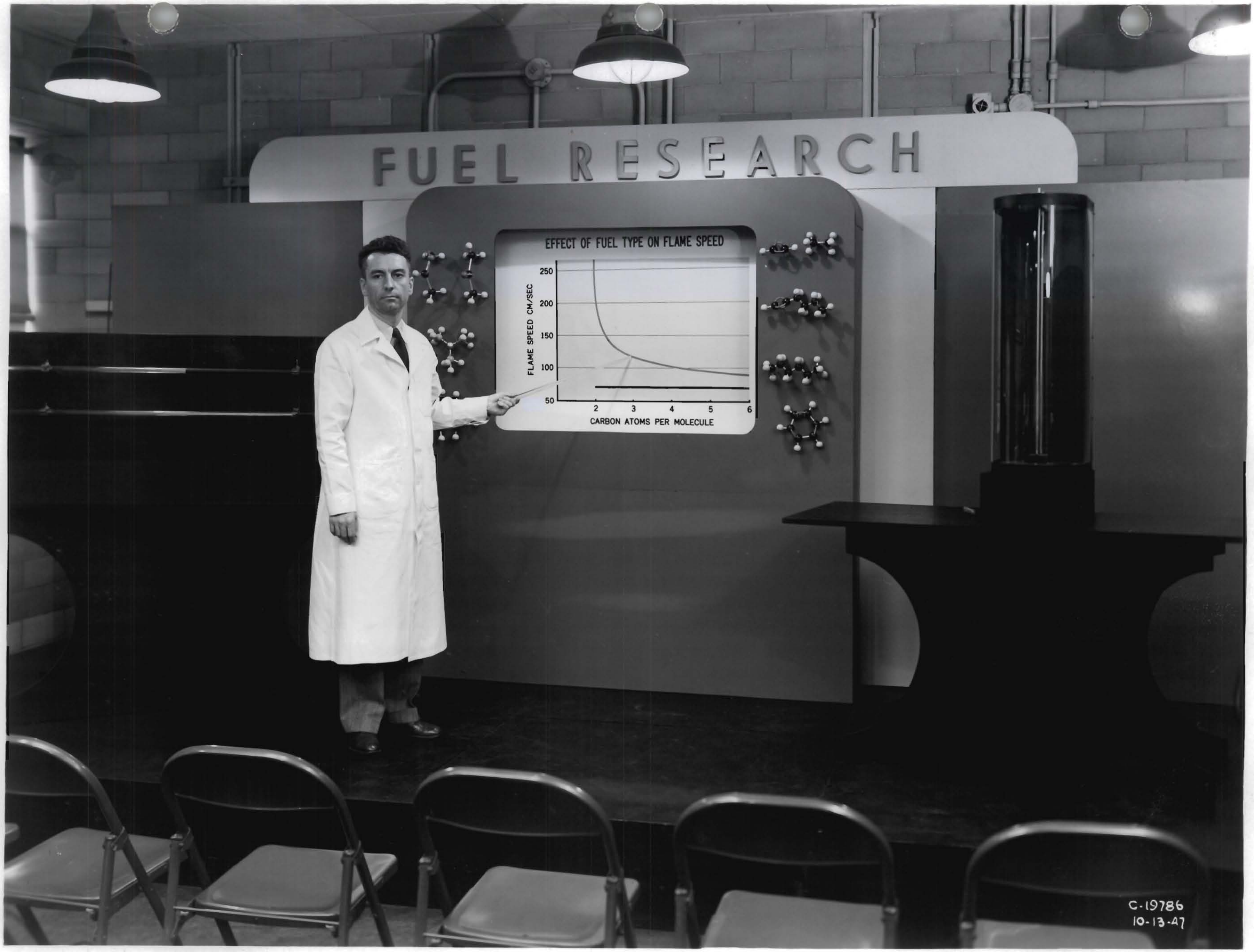

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COMBUSTION VARIABLES INFLUENCED BY FUEL TYPE

COMBUSTION EFFICIENCY

ALTITUDE OPERATIONAL LIMIT

FLAME SPEED

EASE OF IGNITION

ENERGY PER UNIT VOLUME

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Fig 43

VARIATION OF COMBUSTION EFFICIENCY WITH INCREASING ALTITUDE

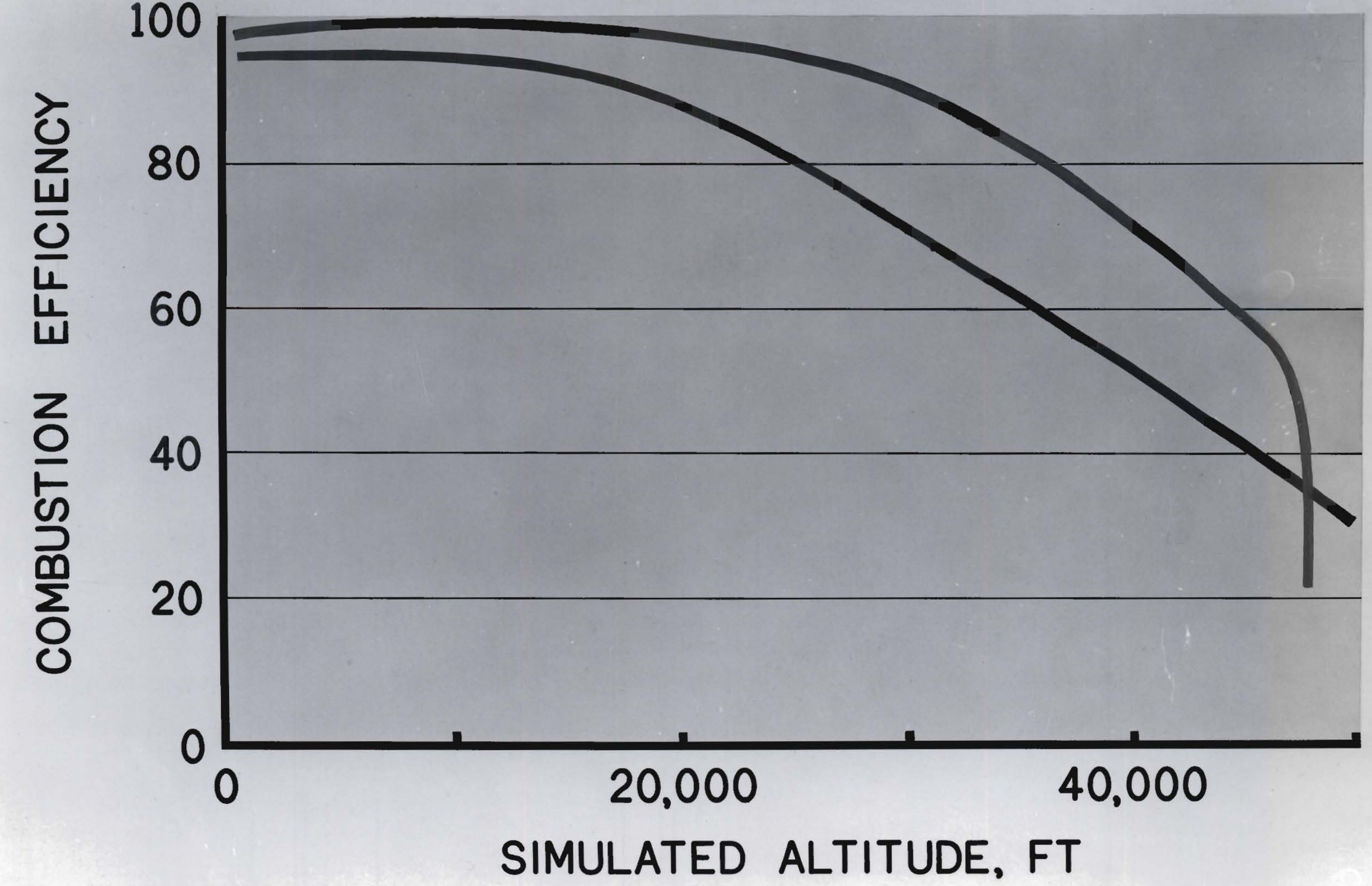

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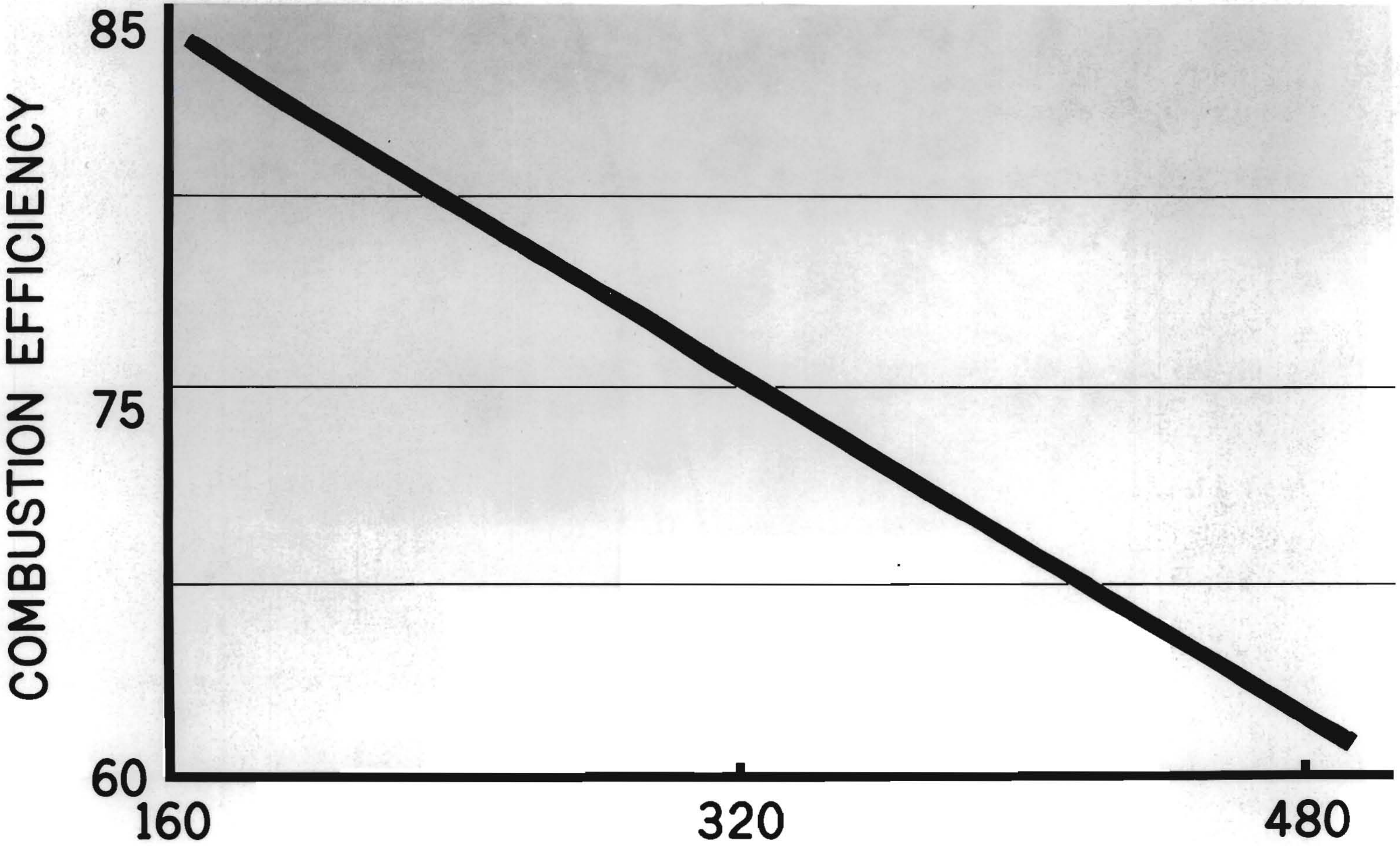
Fig 44

INFLUENCE OF BOILING POINT ON COMBUSTION EFFICIENCY AT ALTITUDE CONDITIONS



AVERAGE BOILING POINT °F

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Fig 45

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ALTITUDES ATTAINED WITH GASOLINE AND KEROSENE IN VARIOUS COMBUSTORS

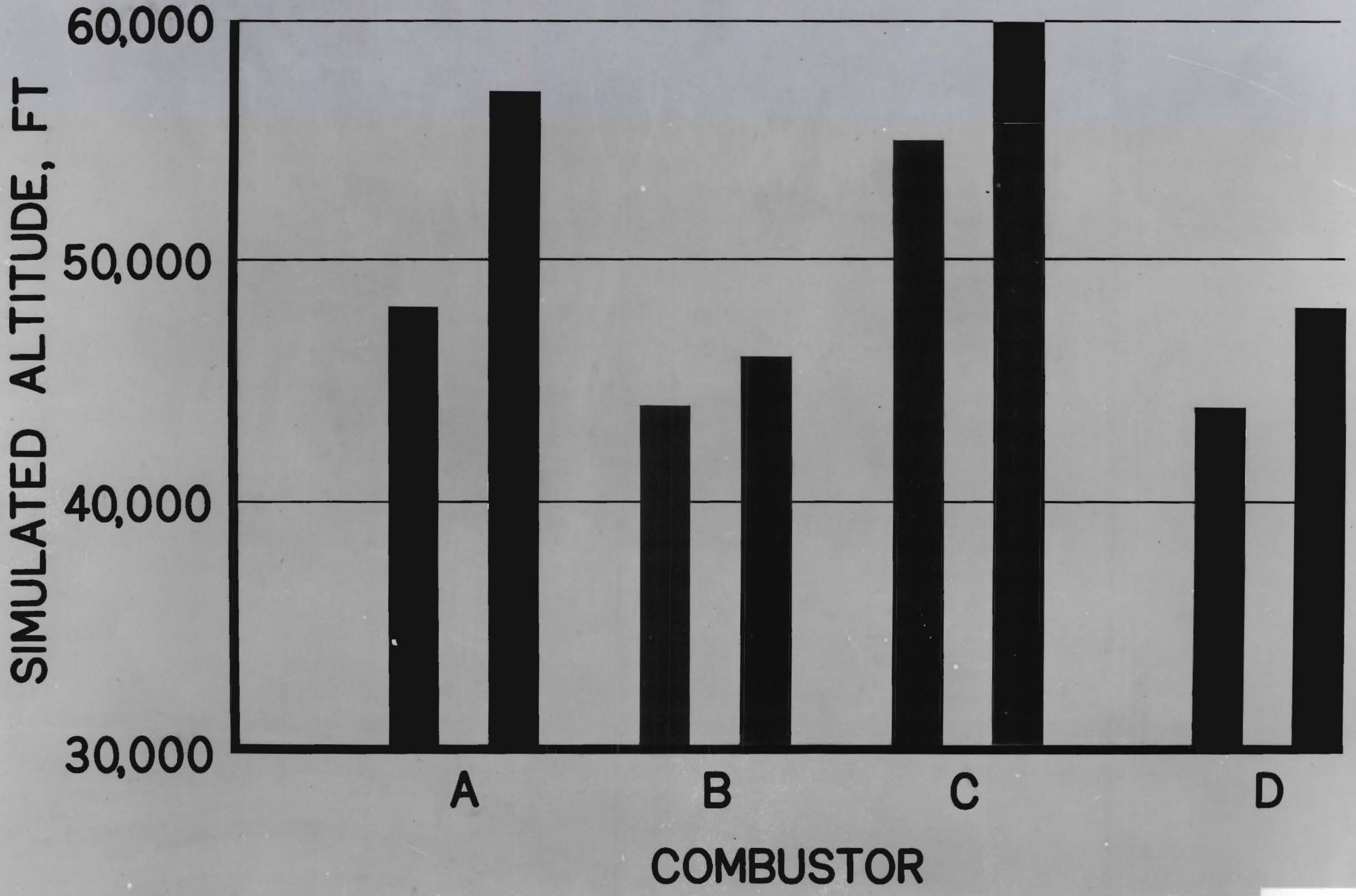

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Fig 46

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EFFECT OF FUEL TYPE ON FLAME SPEED

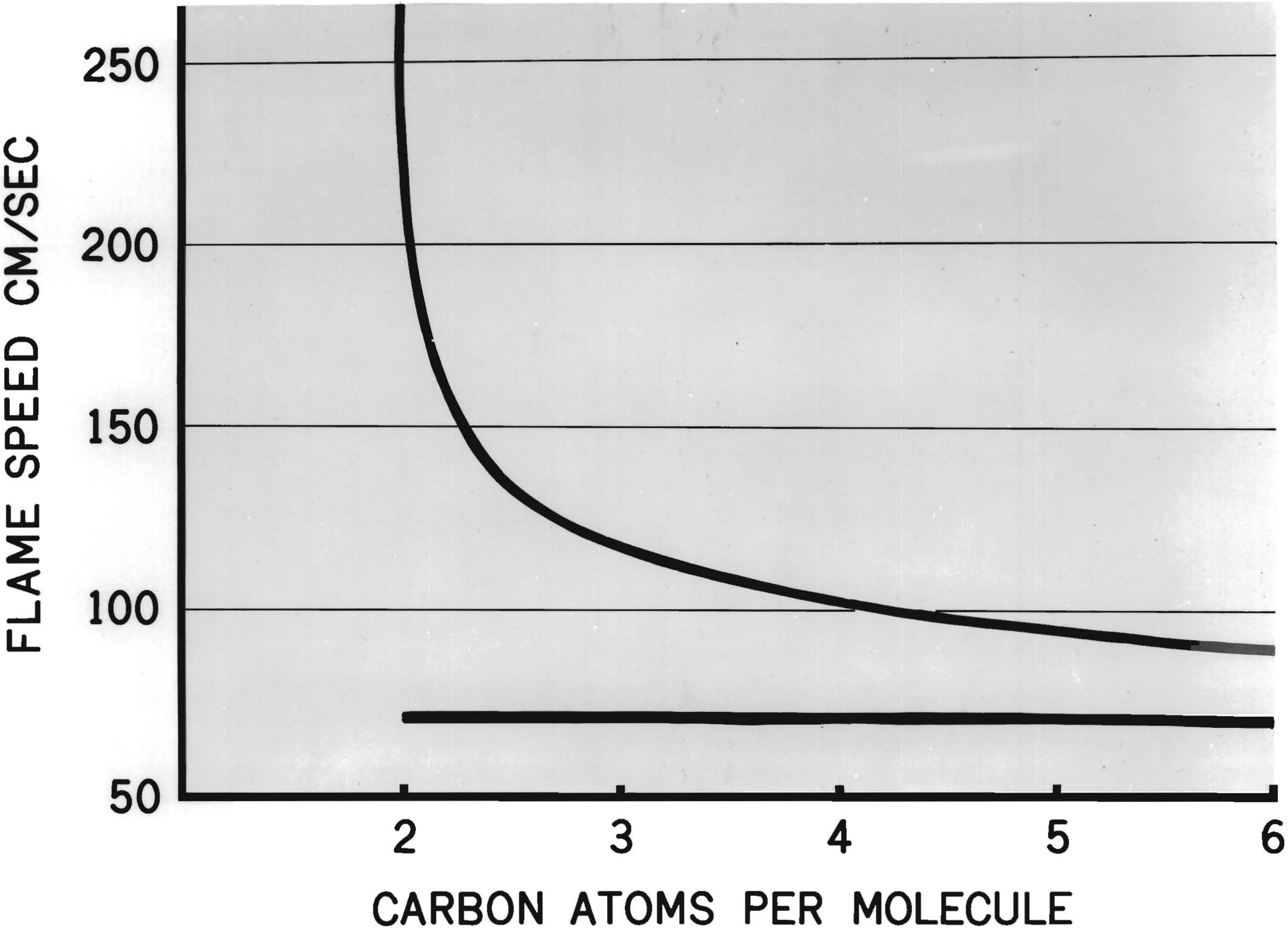

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Fig 47

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HIGH ENERGY FUELS

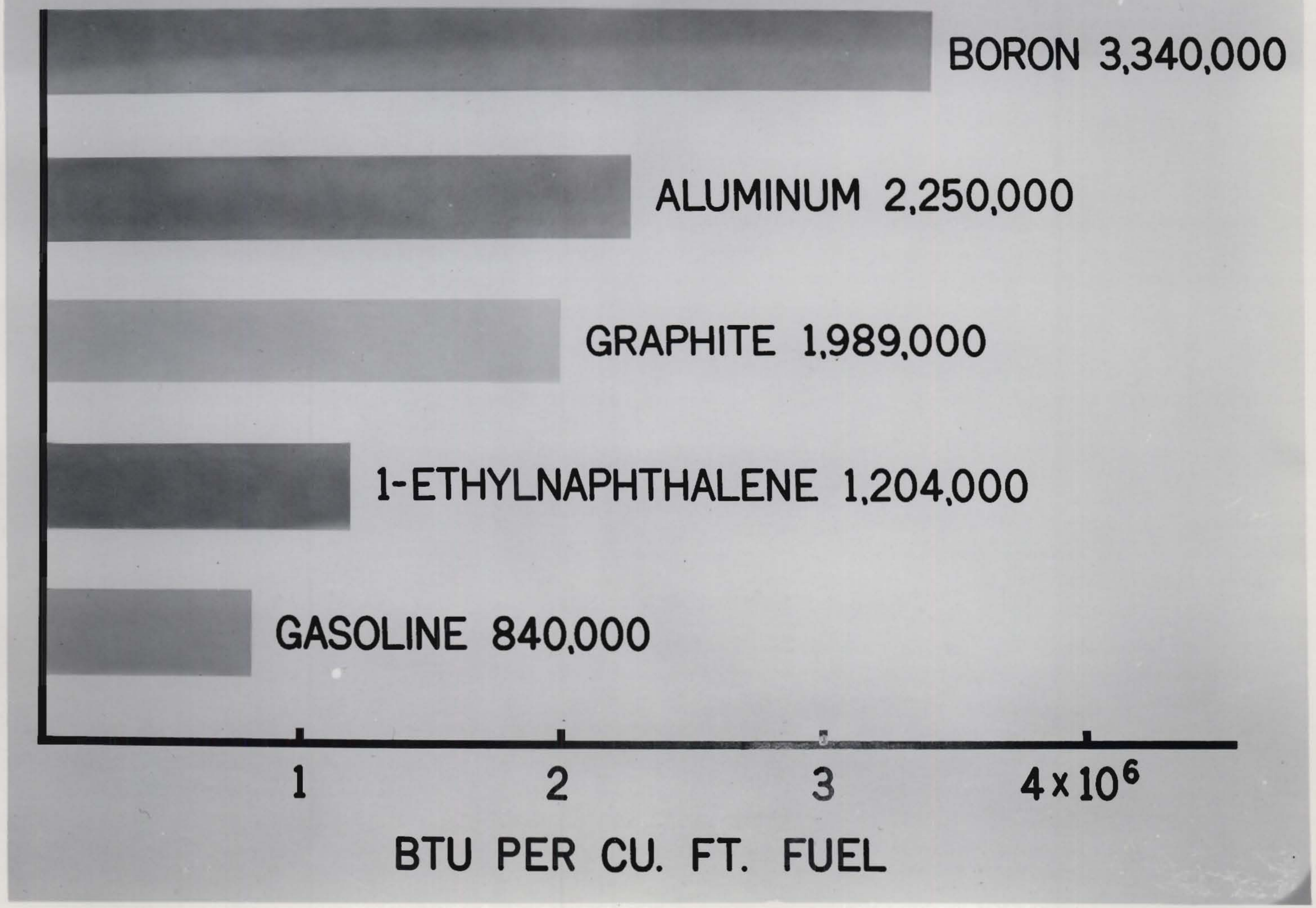

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Fig 48

COMPARISON OF ENERGY RELEASE

	BTU / CU. FT.
GASOLINE	840,000
NAPHTHALENES	1,200,000
BORON	3,340,000
URANIUM FISSION	40,000,000,000,000

C- 19743
10-9-47

Fig 49

Combustion Research
(For First Annual Inspection)
October 8, 9, and 10, 1947

by Walter T. Olson

Part of the program of engine research in general at the NACA is combustion research in particular. There are two, complimentary, major objectives in the combustion research program, one of which is to learn the basic physics and chemistry of burning, and the other of which is to learn the performance characteristics and design criterions of combustion chambers for aircraft gas turbines, ramjets, rockets, and other propulsive devices. We want to find out just what happens when fuel and air react, and we want to find out how combustion chambers operate, and how they should be designed so that they will operate in the way that is desired. In order to indicate the general nature of the NACA's program on combustion research we shall illustrate with a discussion of research on combustion chambers for aircraft gas turbines. That is, the particular case for the combustor of the gas turbine is being selected from the broad combustion research program to illustrate for you the nature of that broad program.

Shown in Center of Fi 50 behind demonstrator

The combustor is the very heart of the aircraft gas turbine engine. It is here that the chemical energy stored up in the fuel is released as kinetic energy to operate the engine and to drive the airplane. This figure, that is a cut-away view of the gas turbine used as a turbojet, can be used to show how a combustion chamber works. Air is compressed by the compressor and passes into the combustor. Part of this air enters the upstream end of a flame tube or basket in the combustor through small holes in the walls of the flame tube or basket. Fuel is sprayed into the air, ignited with a spark plug, and burns continuously. The rest of the air that has entered the combustor passes through more holes farther downstream in the basket, mixes with the burning gases, puts out the flame, and brings the temperature of the gas down to values that can be tolerated by the blading in the stator and turbine. (Demonstrate.) That is how the combustor works.

There are a number of requirements on the combustion chamber. It has to release a lot of heat in a small volume and in a short space of time. Heat release rates in combustors for jet engines are about 100 times the rate of your domestic gas burner. On display here is an example of an annular-type combustor (19XB). This is a ring of fuel nozzles. It is located around the shaft of the engine which occupies this position. (Demonstrate.) The flame tube or basket fits on to the fuel nozzles and the outer casing fits over the flame tube or basket. (More demonstration.) Judging from the rate at which I shoveled coal last winter, this particular combustion chamber would heat about 650 such houses. Not only must the combustion chamber have a high heat release rate, but the flame must be stable and efficient over all conditions for which the combustor is required to operate. In other words, the fire should not go out and all of the fuel should be burned no matter at what speed or altitude the engine runs. The temperature distribution across the outlet of the combustor must follow a desired pattern, or profile, in order that the blading in the stator and turbine not fail. In other words, the stator and turbine blading should not be subjected to extraordinarily hot zones or cores of gas. The pressure put into the air stream by the compressor should not be lost from the air stream as the air flows through the combustor, if the over-all performance of the engine is not to be impaired. And finally, of course, the combustor should be light, durable, and should operate free of carbon deposits, etc. The big problem of the turbojet combustor is to learn how it operates and then to learn how to design it to meet the requirements just outlined.

As an example of the sort of thing that the NACA is finding out about how combustors operate, let me cite that in the Altitude Wind Tunnel it was learned that a turbojet engine would not fly to higher and higher altitudes indefinitely. It is not surprising to find a ceiling on an engine; but it was learned in the Altitude Wind Tunnel that the ceiling on turbojet engines was imposed by the combustion process. Immediately then it became necessary to isolate the combustor from the engine, to set it up in an experimental duct in such a way that the conditions of altitude and engine speed could be simulated for the combustor, and to study its performance in detail in order to learn the causes, and thus to learn the cures for the combustion-imposed altitude operational limit.

An installation of this sort is behind the panel board on your left. Note the large ducting for providing inlet air at various temperatures, pressures, and flow rates, the extensive instrumentation at inlet and outlet of combustor, and the large exhaust duct for simulating the low pressures of high altitude. I do not know of any facility in this country that could have given the complete picture of combustor performance permitted by the facilities right here at this laboratory. Last June I made an extensive tour of the aircraft gas turbine industry in England and nowhere in England are there facilities for testing and evaluating and studying engines and components of engines that can even begin to compare with those of the NACA.

This curve Fig. 51 illustrates altitude operational limits. Shown here is a curve dividing the engine speeds and altitudes below which an engine can operate from those above which the engine cannot operate because of failure of the combustion process. (Demonstrate.) The exact position of the altitude operational limit curve with respect to altitude is, of course, different for different engines for different combustion chambers. The curve is characteristic, however, of all turbojet engines.

To see how the combustion process brings about these altitude operational limits, refer to this next figure Fig. 52 in which is plotted combustor temperature rise versus fuel-air ratio. If the throttle is opened, fuel-air ratio is increased. If the throttle is open and fuel-air ratio increased, the temperature rise of the gases going through the combustor should increase along this line called "theoretical". Let us also show that the engine requires this much temperature rise to operate (demonstrate with "temperature rise required"). If the engine is operating at a speed and altitude favorable to combustion and the throttle is open, the temperature rise should increase along a curve such as this one which very nearly approaches the "theoretical" curve. (Demonstrate.) If the engine is operating at a higher altitude where the conditions of the air at the inlet to the combustor are less favorable for the combustion process and the throttle is opened, a curve such as this next one may result. It is noted here that temperature rise reaches a maximum. In the illustration used this maximum is just enough to operate the engine; there is no temperature rise left over with which to accelerate the engine. Now if you can imagine that somehow the engine could be taken to a still higher altitude where conditions at the inlet to the combustor are still less favorable to combustion, this curve would result. Note here that not enough temperature rise can be obtained to run the engine. In research with the combustor, it was also learned how the conditions of air at the combustor inlet caused these various cases of obtainable temperature rise. In short, the conditions of the air at the inlet to the combustor determine whether or not the combustor will furnish sufficient temperature to operate the engine. Whether or not the combustor furnishes sufficient temperature to run the engine determines whether the engine is below or above its altitude operational limit.

The foregoing illustrated the sort of thing that the NACA is finding out about how combustors operate. Now let us illustrate the nature of the design criterions that are being learned for combustors.

On display here are the annular combustor already described and a can-type combustor. In an engine such as the J-33, or I-40, engine that you say displayed this morning, there are a number of can-type combustors placed around the axis of the engine between the compressor and turbine instead of the single annular combustor. Research on a number of combustors both of can type and annular type and of both U.S. and German origin, indicate that insofar as can type versus annular type is concerned there do not appear to be distinct advantages or disadvantages accruing directly to one type in preference to the other. That is, in the present state of the art, the can type and annular type combustors show equal potentiality for future development. That is an example of one design rule that the NACA has learned.

One of the important things to know is just how to permit the air to flow through the walls of the flame tube or basket, that is, just how should the air flow be distributed along the length of the flame tube or basket? Systematic research on this point has been done by using different series of combustor baskets. In each series the air flow into the combustor basket was varied systematically from basket to basket. On display are three baskets taken from one of these series (24C-4WA). In this particular series eleven baskets in all were involved. These three illustrate the nature of the work. In the first basket it is noted that air is distributed rather uniformly from the inlet end of the basket to the outlet end. The altitude operational limits for this basket are shown in this figure of altitude versus engine speed. (Demonstrate basket A.) This next basket shows some of the air blocked off at the upstream end of the basket. The altitude limits for this basket are slightly higher. (Demonstrate basket B.) In this third basket is illustrated a design rule learned from this series and from other similar series of baskets investigated. (Demonstrate basket C.) The design rule illustrated here is that about 25 percent of the air flowing into the combustor should be admitted gradually, and in about half or more of the combustor length. Note how the progression of small holes from the inlet end of the basket down to the middle of the basket follows this design rule. The altitude limits of this basket are, of course, the highest of the three examples selected.

Fig. 53

These other three baskets are further illustrative of design information that is evolving from NACA research. These baskets are 60° segments of the full annular basket shown on your left (19XB). A segment is used because in many cases it is more convenient to work with a small unit. In the first example selected from a large number of segmental baskets investigated note that air flow is fairly uniform from inlet end to outlet end of the basket. In this next example the air flow is still uniform but the holes are smaller, resulting in more pressure drop and therefore more turbulence and mixing inside the basket. This example has slightly higher altitude operational limits than the first one just shown. The trouble with this second example is that we have increased the pressure drop, and it will be recalled it is desired to keep pressure drop low in order that the over-all performance of the engine not be impaired. This third example from the same series shows the design rule of admitting 25 percent of the air in half or more of the basket length applied. The holes in this basket are sufficiently large so that its pressure loss is low, about the same as for the first of these three segments. The altitude operational limits are the highest for this basket of the three. Interestingly enough by delaying admission of the secondary or dilution air to the basket we have pushed ourselves into another problem. There is in this basket (example 3) no longer sufficient time or distance for good mixing of the gases leaving the combustor, and the temperature distribution at the outlet of the combustor is quite nonuniform and may be detrimental to the life of the stator and turbine blading. That means that we must investigate ways and means of admitting air through the basket wall so that it will mix well and will produce a preferred outlet temperature distribution. Such a program is currently underway.

To learn further the nature of the entire chain of processes going on in the combustor, the individual processes of the fuel spray and the evaporization of the fuel spray, the combustion itself, and the mixing of the gas streams are being isolated in basic research experiments for individual study. (Demonstrate on figure of jet engine.) All of these individual studies are required in order that the entire phenomenon of combustion can be understood more completely and thus better utilized for flight propulsion.

We have now illustrated for you the nature of the combustion program at the NACA by discussing in some detail the performance characteristics and a few of the design criterions for the combustor for aircraft gas turbines. In order to show you what you would see should you look into a turbojet combustor while it is operating, Mr. A. O. Tischler will present a colored motion picture. Mr. Tischler.

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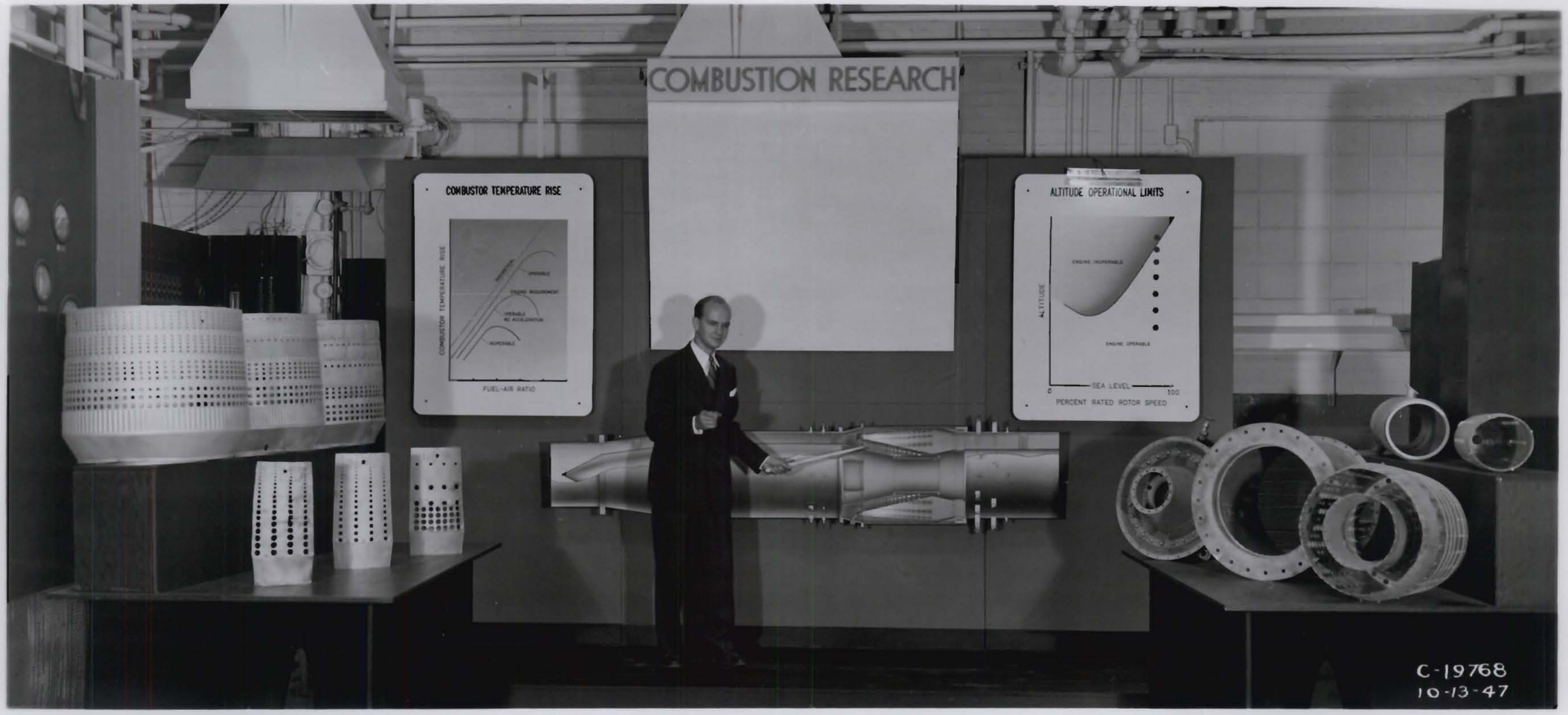
COMBUSTION RESEARCH
COMBUSTOR TEMPERATURE RISE
COMBUSTOR TEMPERATURE RISE
OPERABLE
ENGINE REQUIREMENT
OPERABLE
NO ACCELERATION
INOPERABLE
FUEL-AIR RATIO
ALTITUDE OPERATIONAL LIMITS
ENGINE INOPERABLE
ALTITUDE
ENGINE OPERABLE
SEA LEVEL
0
100
PERCENT RATED ROTOR SPEED
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Fig 50

ALTITUDE OPERATIONAL LIMITS

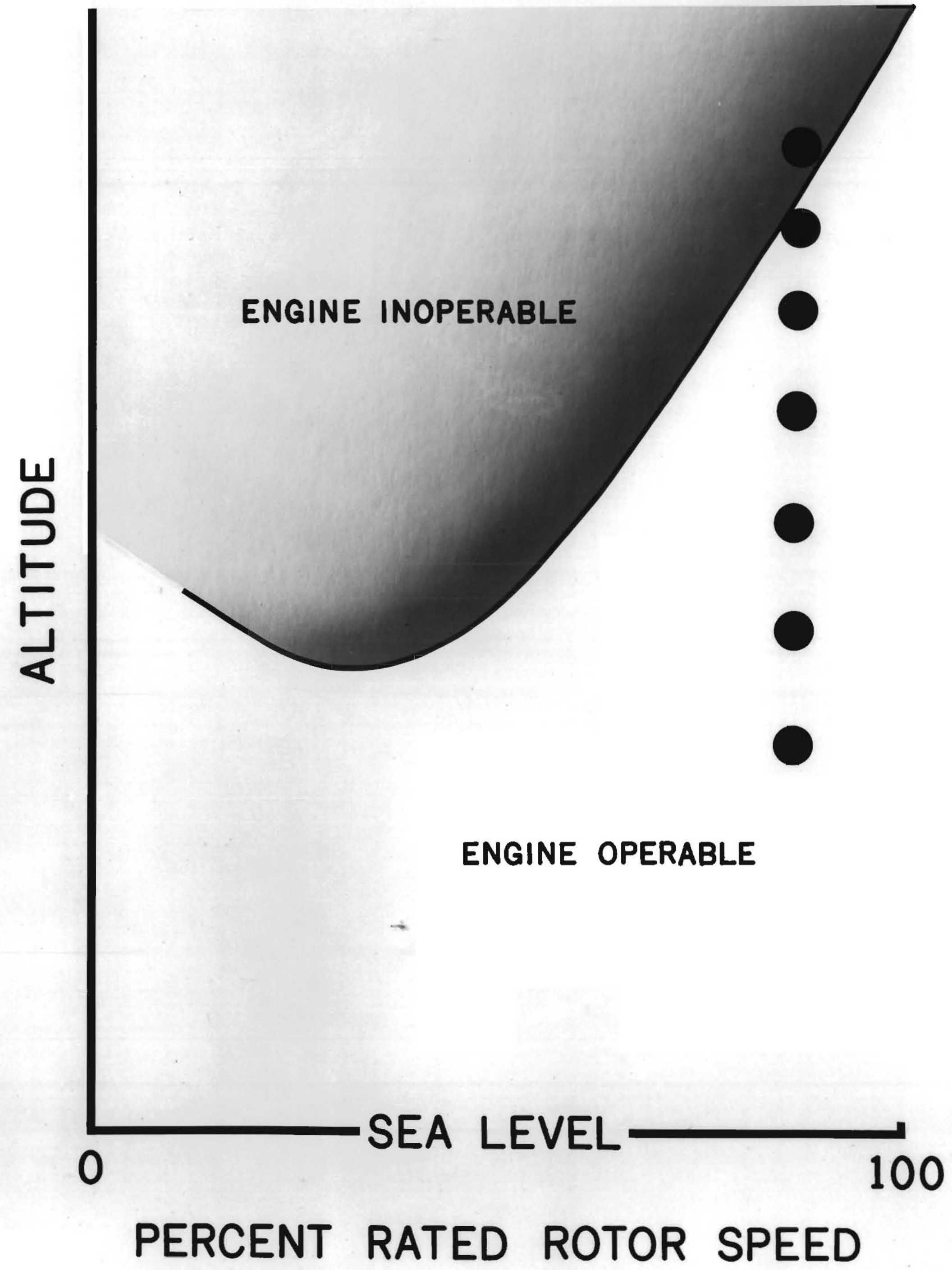

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Fig 51

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COMBUSTOR TEMPERATURE RISE

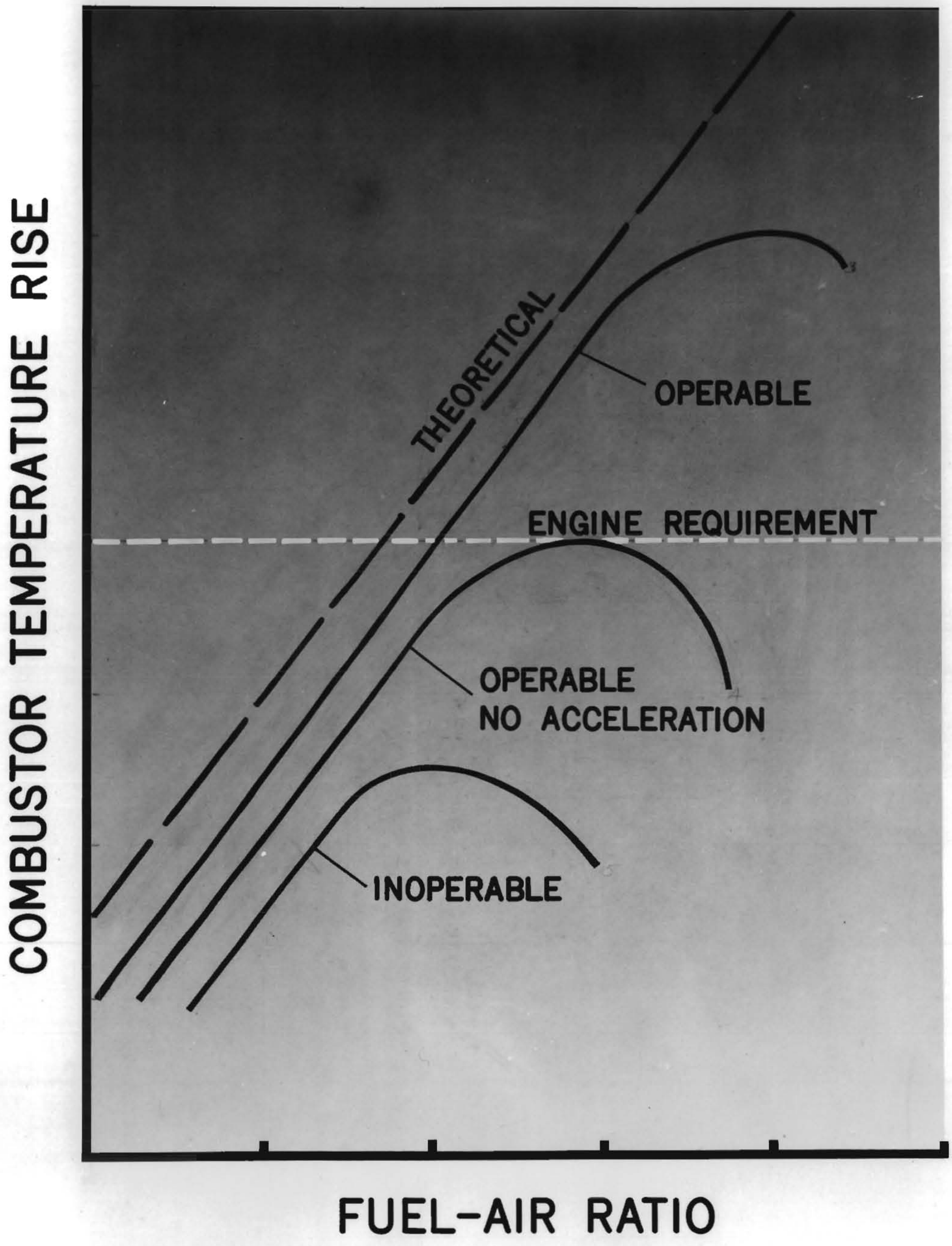

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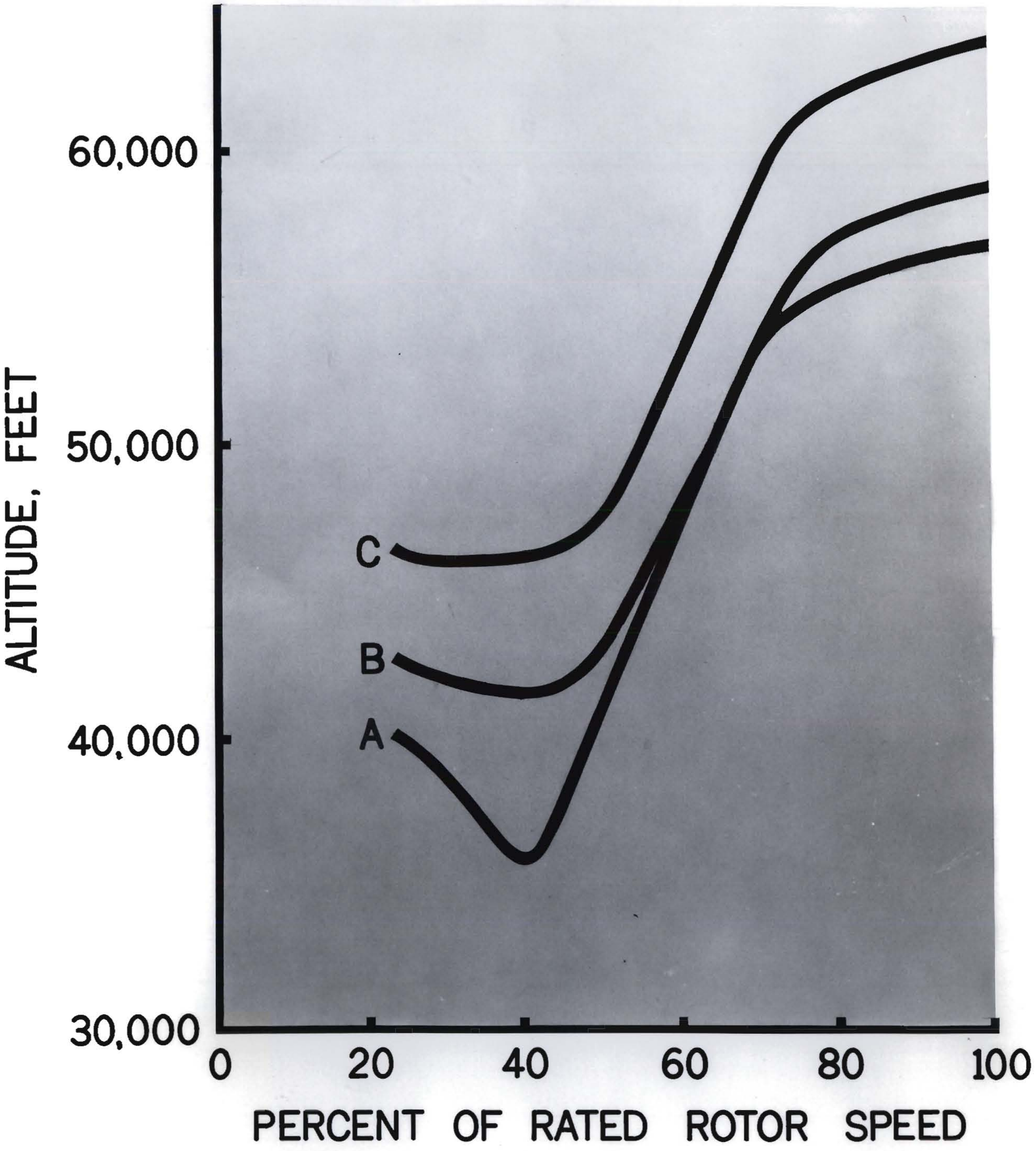
Fig 52

ALTITUDE OPERATIONAL LIMITS OF THREE COMBUSTORS



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NACA

Fig 53

Combustion Research
(For First Annual Inspection)
October 8, 9, and 10, 1947

by Adelbert O. Tischler

In order to illustrate the appearance of the flame in a turbojet combustor as the altitude of the engine is increased, colored motion pictures of the flame in the combustor were taken over a range of simulated engine speeds and altitudes. The combustor setup used to obtain these photographs is that in the adjoining test cell (CW-5A). The camera position was downstream of the combustor looking upstream through the exhaust duct to see the flame in the combustor basket; consequently, the combustion appears in the photographs as an annular ring of flame.

The motion pictures were taken at inlet-air conditions to the combustor which simulated operation at a fixed engine speed and over a range of altitudes, as indicated by the dots on the altitude operating limit chart. The first scene will show combustion at an altitude of 25,000 feet and succeeding scenes will show combustion at altitudes increasing in steps of 5000 feet up to an altitude of 45,000 feet. The second last scene will show combustion at an altitude of 47,000 feet which is just below the altitude limit of operation for this particular engine and the last scene will show operation above the altitude limit.

At an altitude of 25,000 feet the flame in the combustor is very steady and its color is orange-yellow, similar to the color of a match or candle flame. The combustion efficiency at this altitude, well below the altitude limit, is 99 percent.

The large rods which appear to cross the flame radially are support struts for the exhaust cone of the engine. The pencil-size rods are exhaust-gas thermocouples and pressure-tube instrumentation.

At 30,000 feet altitude the color of the flame is yellow. The combustion efficiency has descreased to 96 percent.

At 35,000 feet altitude the flame, though still substantially yellow, is tinged with flecks of blue flame. The combustion efficiency is now only 91 percent.

At 40,000 feet the combustion efficiency is 85 percent and the blue colored flame is predominant. Note that as the altitude is increased the flame appears progressively more blue and the combustion efficiency drops off. This is characteristic of turbojet engine combustion but flame color is not necessarily an indication of combustion efficiency.

At 45,000 feet any yellow flames are almost entirely absent; the combustion efficiency is 70 percent. The blue color is similar to that of a well-adjusted domestic gas-burner flame. More and more intense flickering of the flame is noticeable at each of the successively higher altitudes.

At 47,000 feet, just below the altitude limit of operation, the flame is almost entirely blue and flickering. The combustion efficiency is 65 percent.

At 48,000 feet altitude the air passing through the combustor cannot be heated sufficiently to maintain engine speed regardless of the fuel flow. At this altitude the engine has exceeded the combustion imposed altitude operating limit. The flame is blue and very unstable and pulsating. The photographs show the flame leaping down the exhaust duct toward the camera.

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demonstrated is one now in use on a service turbojet engine. The variable-area nozzle is an experimental type designed and built at this Laboratory.

I have now adjusted the flow rate to each of the nozzles to a flow of 50 pounds per hour, which is the minimum employed in actual service on the fixed-area nozzle. The difference in atomization between the two is readily apparent. You will note that the pressure to the fixed area nozzle is so low as to be scarcely indicated by the pressure gage. The pressure to the variable-area nozzle, however, is now at 50 pounds, a pressure high enough to produce good atomization. I have now adjusted the fuel flow to each nozzle to 150 pounds per hour. You will note that the atomization of the fixed-area nozzle has improved but that its pressure has risen sharply to 70 pounds an hour. The pressure to the variable-area nozzle, however, has risen only a few pounds. I have now adjusted the fuel flow to the two nozzles to a flow of 300 pounds per hour. You will note that the pressure to the fixed-area nozzle has now risen to 150 pounds per square inch while the pressure to the variable-area nozzle has again only risen a few pounds.

The advantage of the variable-area nozzle from a standpoint of improved atomization has been known and recognized by workers in the field of jet-engine development almost from the beginning. However, the inherently poor characteristics of variable-area nozzles as metering devices have stood in the way of their application.

The importance of good metering characteristics can be seen by referring to the panel on which we have the essential features of the fuel system currently used on all types of jet engines. The fuel flows from the throttle valve to a manifold from which the fuel is distributed to the several nozzles. The flowmeters connected in this model would not, of course, be present in an actual fuel system. The manifold supplies fuel to all the nozzles at equal pressures and it is the function of the nozzles to control the rate of flow at each pressure such that the flow through all the nozzles is equal. The nozzles must therefore all be matched to give the same rate of flow at equal pressures. This requires close work even with fixed-area nozzles and is relatively impossible with variable-area nozzles because of the difficulty of matching spring rates and flow coefficients over the wide range of areas.

We will illustrate this point on the panel where we have three variable-area nozzles connected to the manifold and a fourth line running to a needle valve. The needle valve will be used to study the effects of variation in nozzle resistance during operation.

The throttle valve will now be opened. You can readily see the unevenness of the fuel distribution. We will mark the flowmeter position for future reference. Now, let us see the effect of a variation in nozzle resistance. The needle valve has now been varied very slightly. As you can readily see, only a slight variation in needle-valve position results

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in a very great change in the distribution pattern. If the resistance of one nozzle should become very low through an operational defect or through a severing of a fuel line, as might occur through battle damage, the fuel pressure in the manifold can drop so low that the flow to the remaining nozzles will be stopped. We can readily see this by opening the needle valve to full open. From this demonstration, it can be seen that the variable-area nozzle, while being desirable from a standpoint of atomization, could not be used in a fuel system similar to that currently in use on jet engines.

In order to use variable-area nozzles, therefore, it will be necessary to control the rate of flow to each nozzle, thereby eliminating the requirement for good metering characteristics. This can be done by substituting a flow-controlling device, which will take the place of the manifold. We have designed and built such a device at this Laboratory, which we will demonstrate shortly. This device, which we have called a fuel-distribution control, will now be installed on the panel in place of the manifold.

While the change is being made, let us refer to this chart. Figure 55 Here we have the pressure-flow relationship of the fixed-area nozzle and the variable-area nozzle that you have just seen demonstrated. For the fixed-area nozzle, the pressure increases rapidly as the flow rate increases. This rate of pressure increase is actually proportional to the square of the increase in flow rate; that is, if the flow rate is increased to twice the original value, the pressure is increased four times. If the flow rate is increased to four times the original value, the pressure is increased 16 times. Some projected engines will require flow ranges of 100 to 1. With a fixed-area nozzle, this would require a pressure rise of 10,000 to 1.

The variable-area nozzle gives us a flow-pressure relationship which is a straight line, as shown on the chart. This enables us to cover wide ranges of fuel-flow rates not only with good atomization but without going to excessive pressure. With the fixed-area nozzle, our system must be designed to operate with the highest pressure required at the highest flow. This highest rate of flow, however, is encountered only at sea-level operation. Because a jet plane is designed primarily for operation at altitude, the engine is operated most of the time at considerably lower fuel flows. Therefore, in spite of the fact that we must carry with us a high-pressure fuel system with all its difficulties and dangers, we are operating for the most part as though we had a low-pressure system with all its disadvantages from the standpoint of atomization. With the variable-area nozzle, however, it is possible to enjoy the benefit of high atomizing pressures at low flows without running into excessively high pressures at high flows. To fully take advantage of this, the slope of the pressure-flow line must be small, somewhat as shown on the chart. Because of this, any slight variation in nozzle calibration, for example, as indicated by the light-line curve, results in very uneven distribution when the nozzles are connected to a manifold which supplies equal pressures to all the nozzles. This has already been borne out in the demonstration that you have just seen.

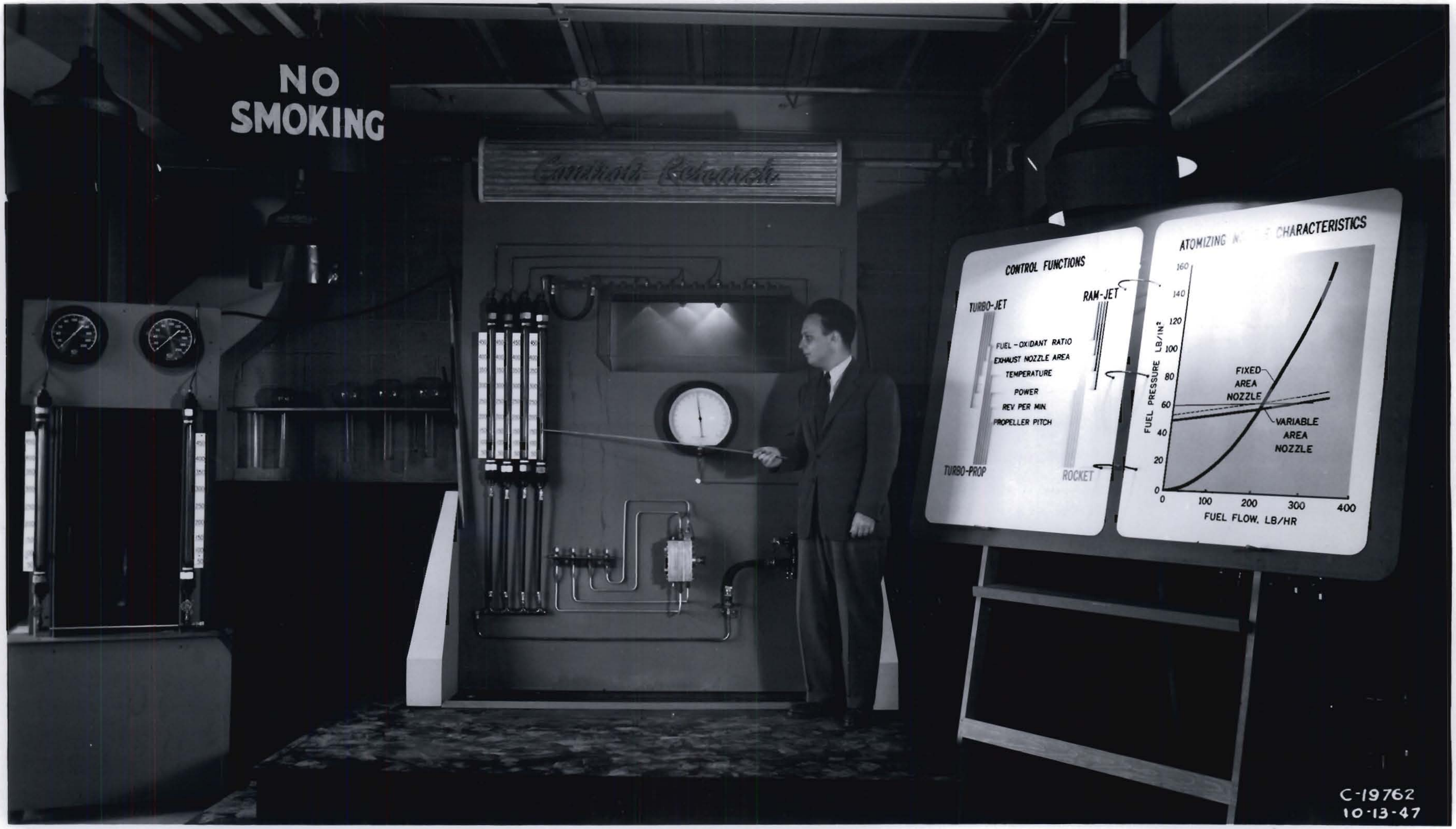
The fuel system on the panel has now been changed and the distribution-control device has been substituted for the manifold. The throttle valve will now be opened and the position of the floats in the flowmeters will again indicate the evenness or unevenness of the distribution. As you can see, the distribution has been vastly improved, and it is apparently perfectly uniform in spite of the uneven resistances of the various nozzles. Referring again to the needle valve to simulating changes in nozzle resistance, you will note that the needle valve can be adjusted at will without any change in the flow in that line. You will note that as the resistance of the needle valve increases, the control automatically increases the pressure in that line in order to maintain the distribution uniform. In full-scale operation, a model of this control in combination with the same nozzles used in the demonstration, maintained the distribution to a jet engine with a maximum deviation from perfect distribution in the order of 2.5 percent over the full range of sea-level-static operation. During these tests, it was found that a remarkable ease of starting was obtained with this system. In addition, it was found that the improved atomization resulted in a reduction in fuel consumption.

Another very interesting phase of control that has grown from our work with this device is in regard to protection against line breakage. It was apparent from the earlier part of this demonstration that with fuel systems of the type currently in use, the breaking of a single line such as might be caused by battle damage, would put the engine completely out of operation. Connected to the distribution control at this point is a small valve which operates on pressures supplied to it by the control. The purpose of this valve is to shut off the flow in this line in the event that the pressure drops below the specified value. It is possible to hook up such a valve with variable-area nozzles because in usual operation the line pressures are always at a reasonably high value.

I will now break this line by pulling off the rubber section. You will note that when the line is broken the fuel flow in that line was immediately shut off. The flow to the remaining nozzles remained undisturbed, and the engine although deprived of the operation of one of the burners would still be capable of maintaining flight.

This concludes the demonstration, and I hope that from it you will have gained some idea of what can be accomplished with automatic control in improving the operational efficiency of aircraft-propulsion systems, and of increasing their safety.

H. Gold
9-29-47
mr



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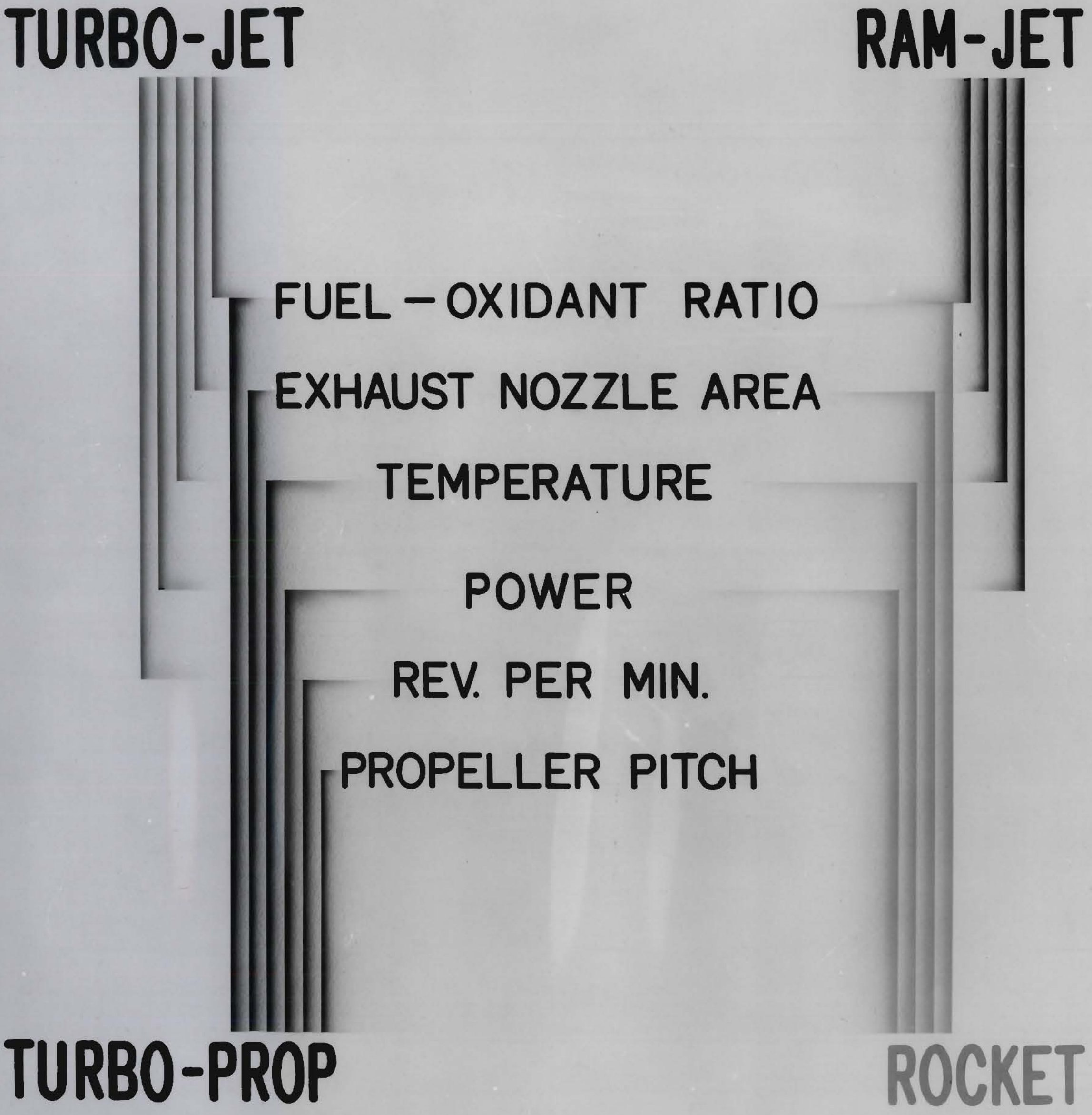
CONTROL FUNCTIONS



TURBO-JET

RAM-JET

FUEL — OXIDANT RATIO

EXHAUST NOZZLE AREA

TEMPERATURE

POWER

REV. PER MIN.

PROPELLER PITCH

TURBO-PROP

ROCKET

C-19885
10-24-47

Fig 54

ATOMIZING NOZZLE CHARACTERISTICS

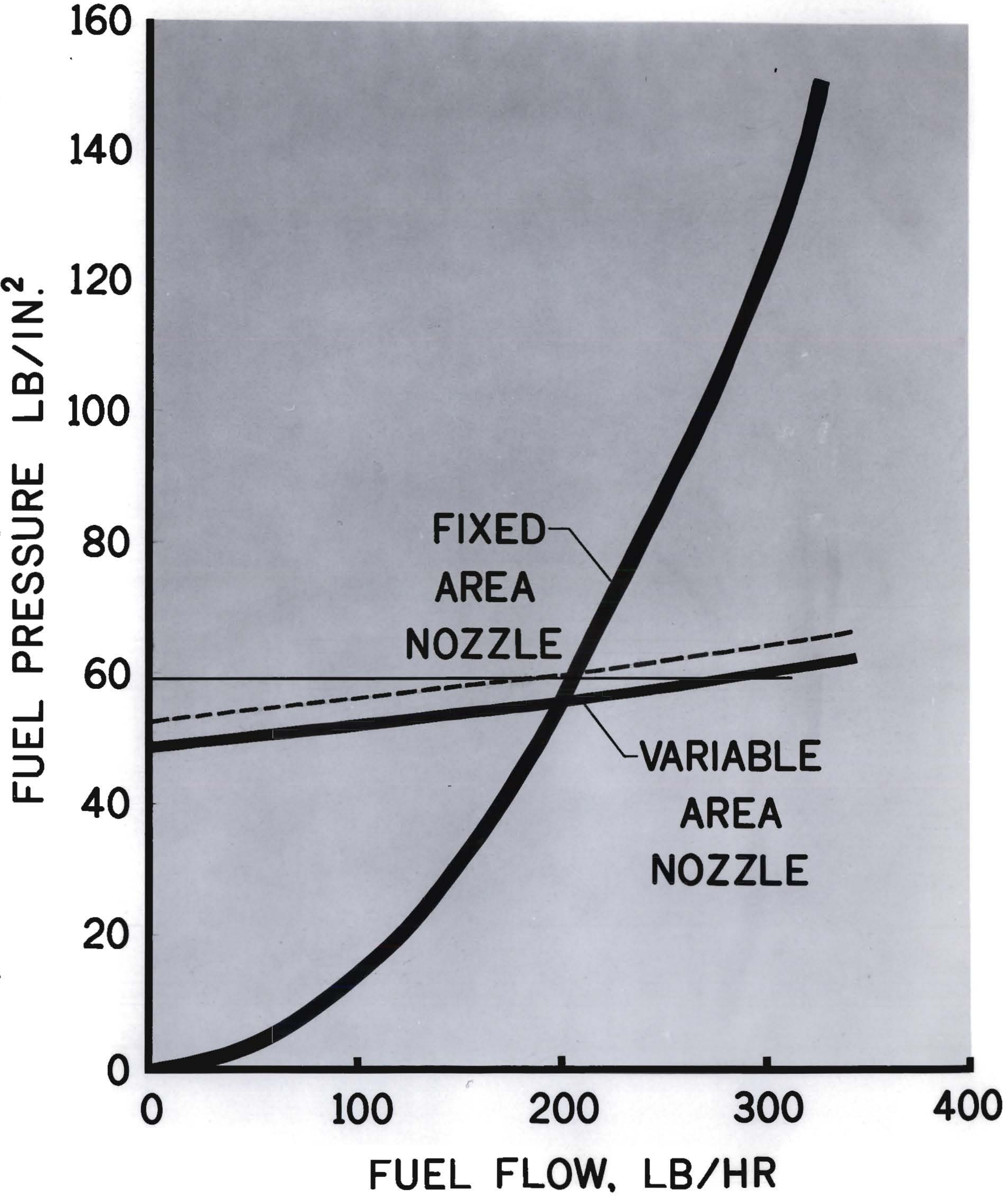


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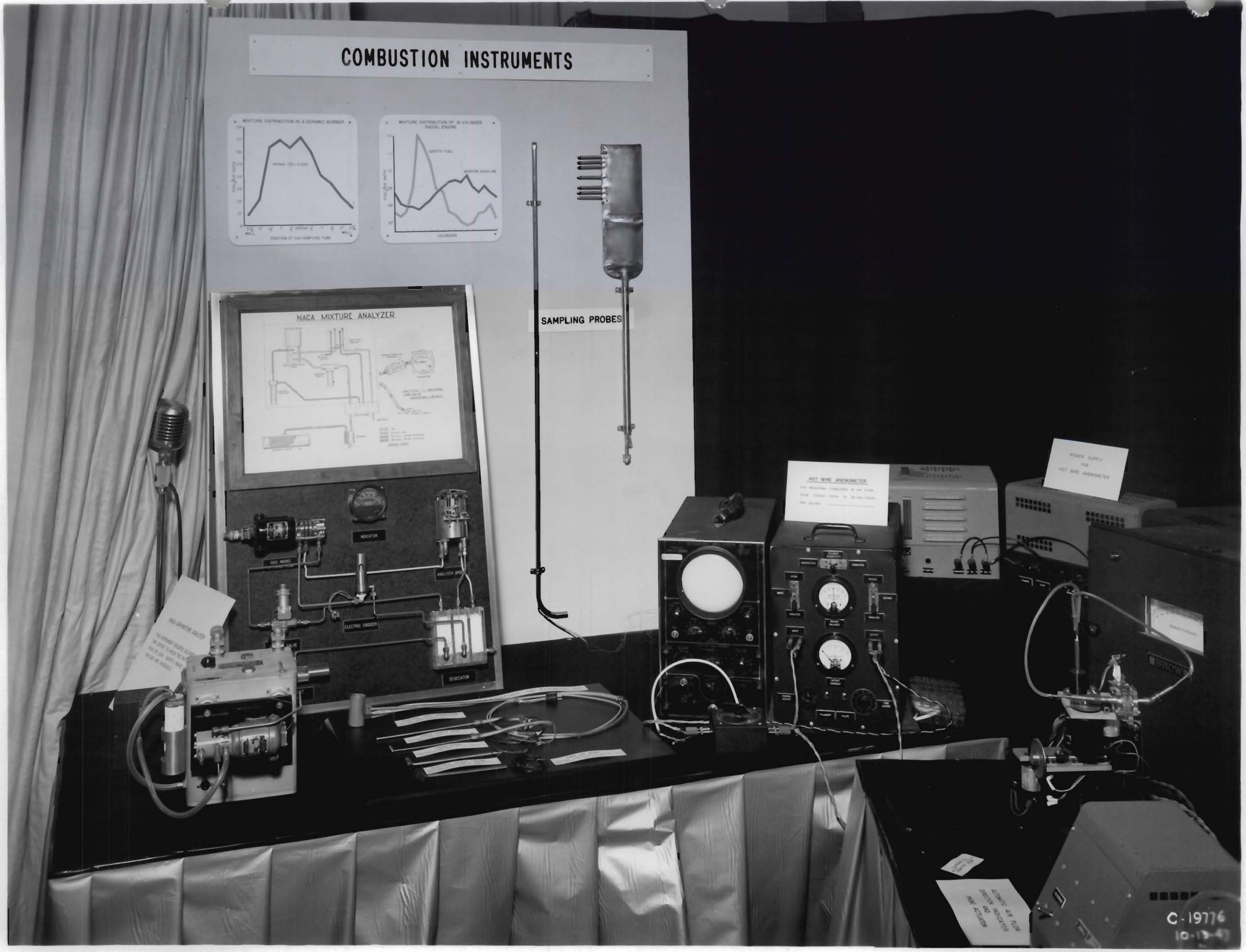
Fig 55


COMBUSTION INSTRUMENTS
MIXTURE DISTRIBUTION IN A CERAMIC BURNER
MIXTURE DISTRIBUTION OF 18-CYLINDER RADIAL ENGINE
SAFETY FUEL
AVIATION GASOLINE
CYLINDERS
POSITION OF GAS SAMPLING TUBE
SAMPLING PROBES
NACA MIXTURE ANALYZER
INDICATOR
GAS MOTOR
ANALYZER
ELECTRIC OXIDIZER
VALVE
DESICCATOR
HOT WIRE ANEMOMETER
POWER SUPPLY
FOR
HOT WIRE ANEMOMETER
BROWN
C-19776
10-13-47

LECTURE FOR ANNUAL INSPECTION

Flight Propulsion Research Laboratory, October 8, 9, and 10, 1947

LUBRICATION, FRICTION, AND WEAR PROBLEMS IN GAS-TURBINE ENGINES

by E. E. Bisson

As you know, the principal part of the gas-turbine-type power plant consists essentially of a simple high-speed rotating element. Because of the obvious simplicity, it was originally assumed that improvements in operation would be easy and that the research problems were not too numerous. Several years of experience have proved this assumption wrong; in fact, the research problems are both numerous and serious.

We are concerned here with research on lubrication, friction, and wear in the gas-turbine-type engine. The problems in lubrication, friction, and wear are all complicated by high speeds and high temperatures. These problems include, among others, those occurring in high-speed bearings, reduction gearing, and seals. Fortunately, from a research standpoint, all these problems could be broken down into basic factors of:

(1) pure sliding

(2) sliding and rolling

(3) pure rolling

(4) high-temperature surface fatigue

For example, in the high-speed anti-friction bearing, pure sliding takes place between the roller or ball and its separator; sliding and rolling takes place between the rolling element and the races because the rollers do not roll at their theoretical rolling speed but they partially slip; and finally surface fatigue takes place. The high-speed journal bearing in normal operation results in pure sliding and, for a very short period of time during the starting process, sliding and rolling takes place. Similarly, in reduction gearing as we consider the location on the tooth surface we obtain almost pure sliding, sliding and rolling, or pure rolling. Again, in glands and seals, we have pure sliding and this under conditions of very low velocity or very high velocity.

The NACA research is concerned then with these basic factors with the primary objectives of determining the fundamental mechanisms involved in the failures in order that the knowledge of these fundamental mechanisms can be applied by all to the solution of their individual, practical problems.

To illustrate, let us take the condition of pure sliding. The NACA research on friction in pure sliding has been done with simple apparatus consisting of a rotating disk on which was pressed a spherical rider or steel ball. It was obvious at the start that it was necessary to work with fundamentals in order to resolve the disagreements and contradictions in the field of friction. The work at the laboratory was made fundamental by the utilization of tools such as electron and X-ray diffraction and the electron microscope to positively identify the condition of the surfaces under investigation.

An analysis was made of requirements of gas turbine power plants, particularly where conditions of high temperature would be encountered and materials for use as surface films were extensively studied in order to determine their worth under these conditions. A large number of materials of all types were included in the research investigation and only a limited number of them will be presented here. The results are presented as plots of coefficient of friction against velocity and it must be remembered, in the interpretation of all data at variable velocities, that an increase in velocity corresponds generally to an increase in temperature at the contacting surfaces. This point is important.

Preliminary investigations here at the laboratory have indicated that solid surface films of the various iron oxides can be associated with good or bad frictional properties and, in consequence, films of this type were included in the experimental investigation. It was found that a natural film of the black oxide Fe_3O_4 formed on run-in or well conditioned surfaces; red oxide Fe_2O_3 was found on non-run-in surfaces, that is, on surfaces which had shown incipient failure. The first chart Fig. 56 shows the results on dry steel and these two oxides of iron. The dry steel curve shows that friction decreases as speed increases. The frictional loss in HP increases slightly over this same range of speeds. Comparison of the curve of steel and ferric oxide (Fe_2O_3) shows that the Fe_2O_3 is not, in general, beneficial from a friction standpoint over the entire range of velocities and definitely not so beyond approximately 4000 feet a minute. Ferroso-ferric oxide (Fe_3O_4), on the other hand, shows a very beneficial result in comparison to both dry steel and Fe_2O_3 over the entire range of velocities. These results agree with those of the preliminary investigation.

As previously mentioned, the conditions of high temperatures in the jet engines will require a supplemental or a dry lubricant which could be best applied in the form of solid surface films. A study of the possible lubricants was made and their physical and chemical properties of most interest are indicated in this next chart. Fig. 57 The items of most interest are the melting point because of high temperature conditions, the hardness of which shear strength is a function, the crystalline structure, the form, the orientation, the solubility in both water and acids, the chemical reactivity and the tenacity for steel. On the basis of some of their previously indicated low temperature friction properties the following materials were considered: molybdenum-disulfide, tungsten-disulfide, graphite, lead iodide, and silver sulfate. A review of their physical and chemical properties shows that lead iodide and silver sulfate might be unsatisfactory because their melting points were too low; they were therefore eliminated. Tungsten-disulfide is very difficult to obtain and it was therefore eliminated.

The only compounds left were molybdenum-disulfide and graphite and it will be seen that these two, besides having high melting points, showed excellent characteristics with respect to properties affecting the friction process. They both had low hardness and consequent low shear strength; they both had the laminated form of structure and both were generally insoluble in many fluids. The molybdenum-disulfide had a decided advantage in that its chemical reactivity was higher than that for graphite which means that under conditions of incipient surface failure some chemical activity could take place and might delay this failure. Also another very important property difference was that the tenacity for steel was high for molybdenum-disulfide and it was low for graphite. This characteristic is very important in film lubricants which are ineffective if they are wiped from the surface.

The next chart Fig. 58 shows the structure of graphite as determined from the electron diffraction pattern indicated. The pattern as shown indicates very highly preferred orientation. The structure is laminated making it easy for surfaces to slip with graphite between them because of the slip planes in the graphite. As indicated carbon atoms are lined up layered form and an interpretation of the electron diffraction pattern enables us to draw a sketch of the graphite on the surface of the steel. The diffraction pattern tells us that the layers are lined up parallel, in general, to the surface of the steel. An important point to be observed is that there is no bonding of the carbon atoms to the steel.

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The structure of molybdemm-disulfide, on the other hand, is shown in the next chart. Fig. 59 Again the diffraction pattern positively identifies the material and shows random orientation. The molybdenum-disulfide compound occurs as layers of molybdenum atoms flanked on either side by layers of sulfur atoms. The sulfur to steel bond is very good, whereas the sulfur to sulfur bond is very poor. The molybdenum-disulfide particles arrange themselves as shown so that we will have sulfur bonds at the steel surface; after that we have a random orientation. However, since the sulfur to sulfur bonds are very poor, slip can take place between these atoms and resulting friction is low.

The next chart Fig. 60 shows the friction results with these two high-temperature lubricants. Again dry steel is included for comparison. Graphite is shown to have an initially low friction but shows an increase in friction with speed, whereas molybdenum-disulfide also has an initially low friction and decreases in friction with speed. The curve for boundary-lubricated steel is also indicated for comparison and it can be seen that molybdenum-disulfide is nearly as good as the steel lubricated with one of the best polar type compounds. It is probable that the increase in trend with graphite may be explained by the fact that the absorbed water in the graphite which contributes to its low friction is being driven off by the high surface temperatures resulting from increased speeds.

So much for the fundamental research on friction under conditions of pure sliding. The results of this research have provided basic information on friction which can be applied by all to the solution of practical problems. Just as an illustration of the manner in which supplemental lubricants could be utilized at high temperatures, we will now have a demonstration of the effectiveness of molybdenum-disulfide as applied to a practical bearing surface. We have two bearings loaded by weights in the form of wheels and ~~running~~ supported on a rotating steel shaft which is coated with MoS_2 at one of the bearing locations only. For demonstration purposes the rotative speed is low. Both flywheels have cords wrapped around their periphery leading to the weights indicated. These weights serve as restraining forces to keep the wheels from turning with the shaft. As the friction torque increases to the point where the restraining torque is exceeded the weights will lift. Heat will be applied to the two bearings by means of gas burners and the ordinary hydrocarbon lubricant which is now present between the surfaces will be driven out and decomposed. Because of the lack of adequate lubrication then, the bearing at the untreated location will start to fail. As the failure becomes more and more pronounced, the friction torque will increase and the restraining weight will be lifted until it strikes the stop. When seizure or welding of the bearing to shaft takes place, the cord will break and the wheel will rotate with the shaft.

While this bearing at the non-treated location is failing because of inadequate lubrication, the bearing at the treated location is receiving supplemental lubrication from the film of MoS_2 in spite of the fact that the oil is driven out by the heat. As previously shown, the MoS_2 is unaffected by temperatures up to approximately 1100° C (2000° F) and it has low frictional properties at high speeds and loads (which corresponds to high surface temperatures). This bearing then will continue to run smoothly in spite of continued heating.

Thus we have a practical demonstration of the effectiveness of a supplemental lubricant at high operating temperatures. Please remember, however, that this demonstration is for purposes of illustration only and is not to be construed as a recommendation that bearings be operated under these conditions.

In summary, the lubrication, friction, and wear problems in the gas-turbine type engine are broken down into the basic factors involved. The NACA research is concerned with these basic factors and the primary objective is to determine the fundamental mechanisms of failure in order that this fundamental knowledge may be applied to the solution of practical problems. In the gas-turbine engine, since we are confronted with extremes in the operating conditions of speeds, loads, and temperatures, supplemental lubrication may be necessary and this supplemental lubrication can be furnished by solid surface films composed of materials inherently suited for the job. As was demonstrated, results of basic analyses and experimental investigations can be applied to the solution of problems of this nature.

EEBisson
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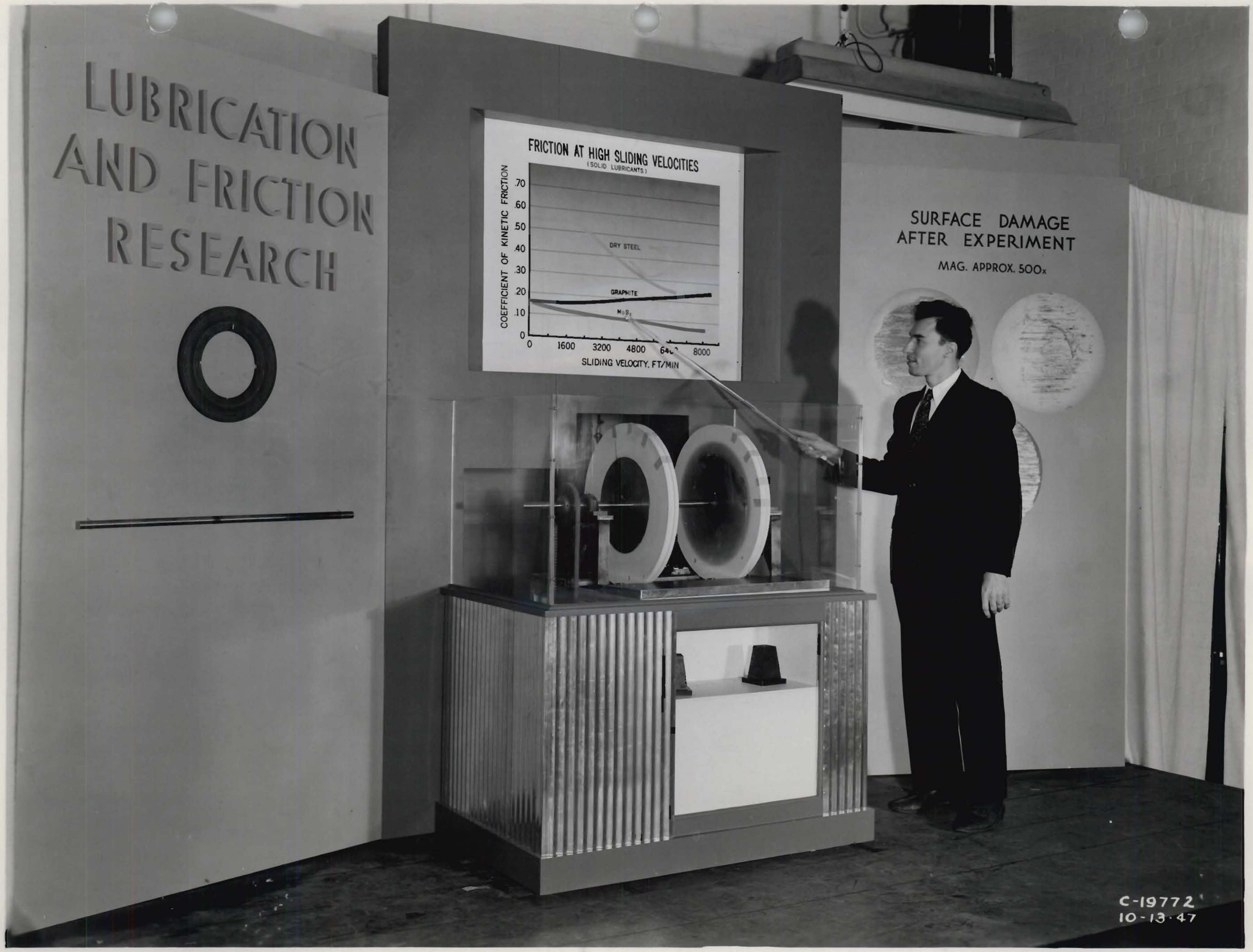

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FRICTION AT HIGH SLIDING VELOCITIES

(IRON OXIDES)

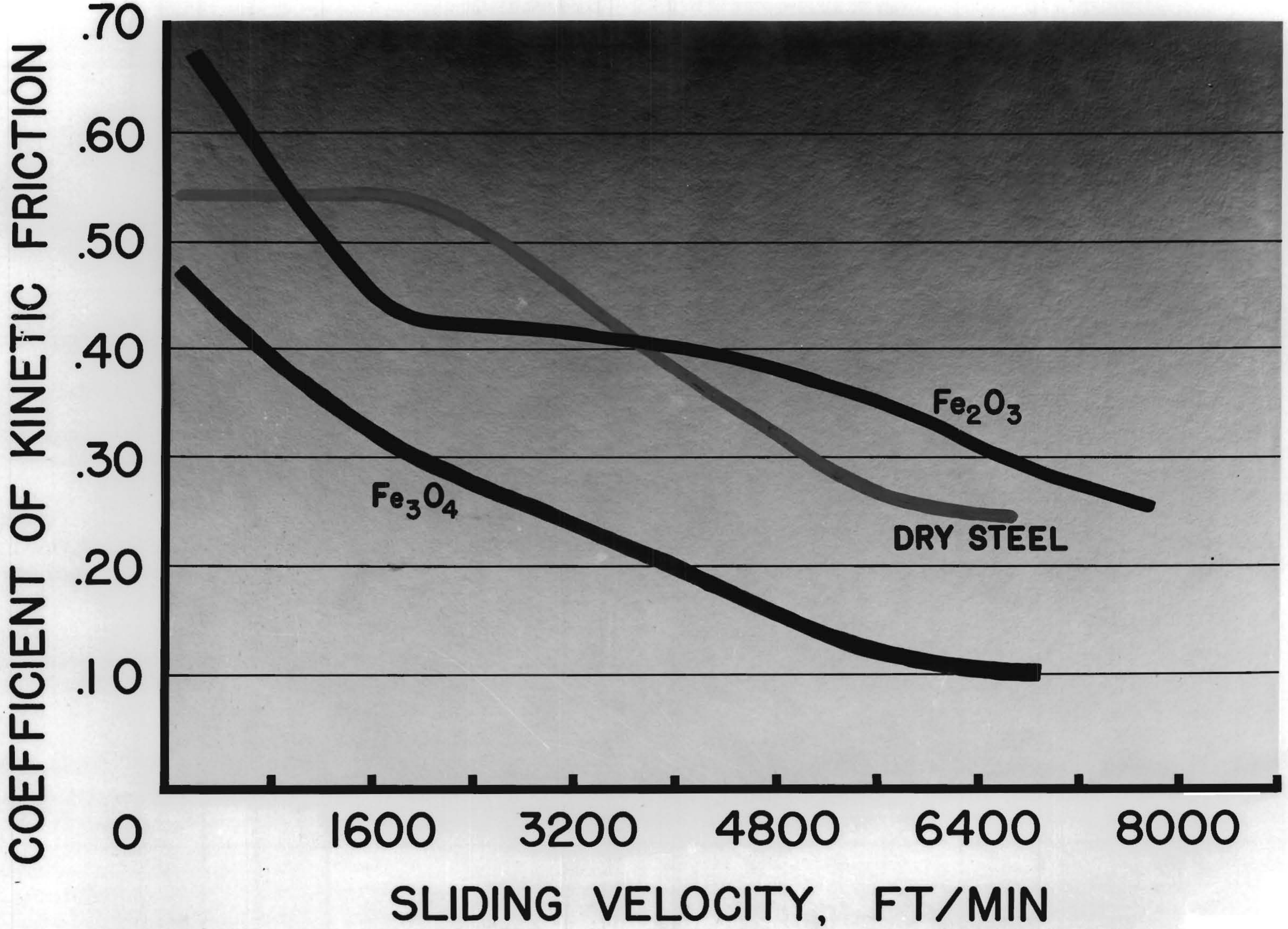

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Fig 56

PHYSICAL AND CHEMICAL PROPERTIES OF SOLID LUBRICANTS

	MOLYBDENUM DISULFIDE MoS_2	TUNGSTEN DISULFIDE WS_2	GRAPHITE C	LEAD IODIDE PbI_2	SILVER SULFATE Ag_2SO_4
MELTING PT. °C	1185	d 1250	3527	402	652
HARDNESS (Mho)	1.0-2.5	FRIABLE	1.0-2.0	-	-
CRYSTALLINE STRUCTURE	HEXAGONAL	HEXAGONAL	HEXAGONAL	HEXAGONAL	ORTHO-RHOMBIC
FORM	LAMINATED	-	LAMINATED	-	-
ORIENTATION	RANDOM	NONE	HIGHLY PREFERRED	NONE	NONE
SOLUBILITY:					
IN WATER	INSOLUBLE	INSOLUBLE	INSOLUBLE	SLIGHTLY	SLIGHTLY
IN ACIDS	H_2SO_4, Ag. Reg.	$HNO_3 + HF$	INSOLUBLE	KI	HNO_3, H_2SO_4
CHEMICAL REACTIVITY	MEDIUM	MEDIUM	LOW	MEDIUM	MEDIUM
TENACITY FOR STEEL	HIGH	MEDIUM	LOW	-	-

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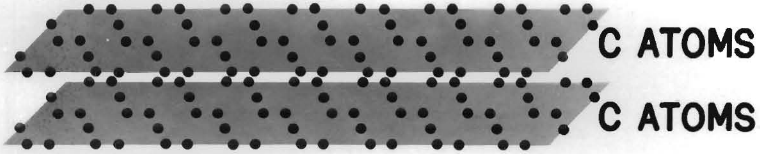
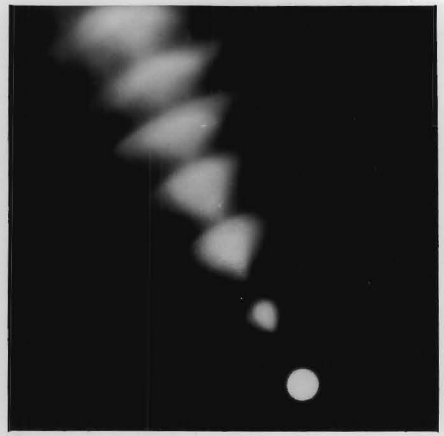
Fig 57

PHYSICAL CHARACTERISTICS OF GRAPHITE



FORM OF LAMINAE



ELECTRON DIFFRACTION PATTERN

SHOWING HIGHLY PREFERRED ORIENTATION

BONDING TO STEEL SURFACE

NO CHEMICAL BONDING TO STEEL SURFACE

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10- 24- 47

Fig 58

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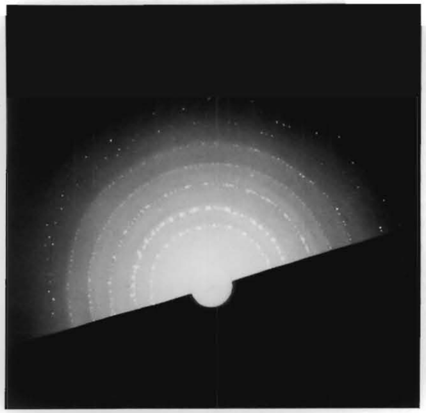
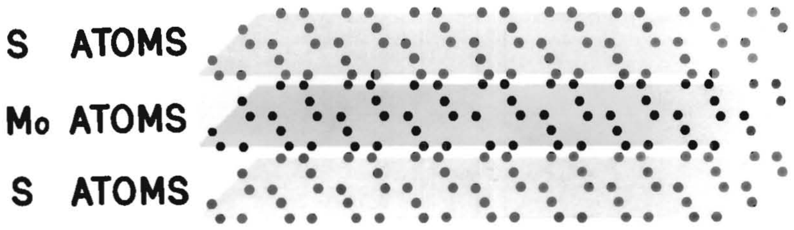
PHYSICAL CHARACTERISTICS OF MOLYBDENUM DISULFIDE

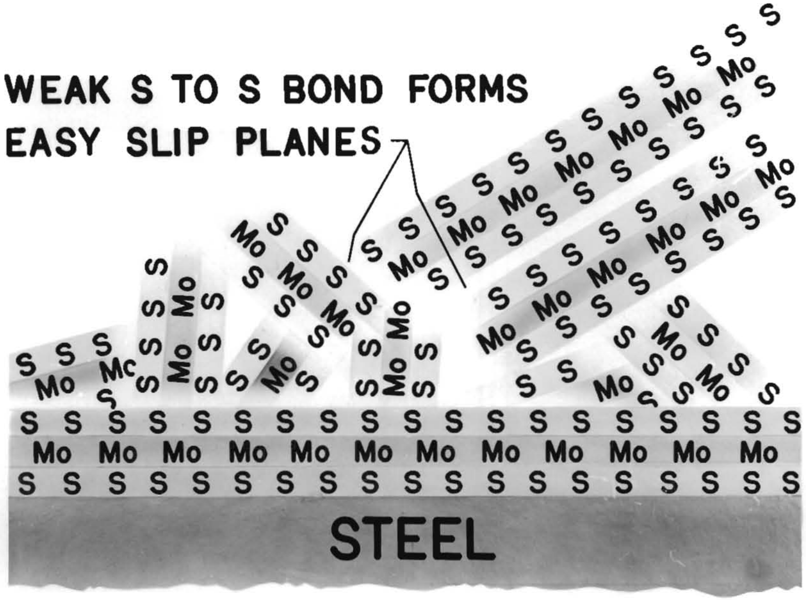


ELECTRON DIFFRACTION PATTERN

SHOWING RANDOM ORIENTATION AND FINE CRYSTALLINITY



FORM OF ONE LAMINA



BONDING TO STEEL SURFACE

STRONG SULFUR TO STEEL BOND

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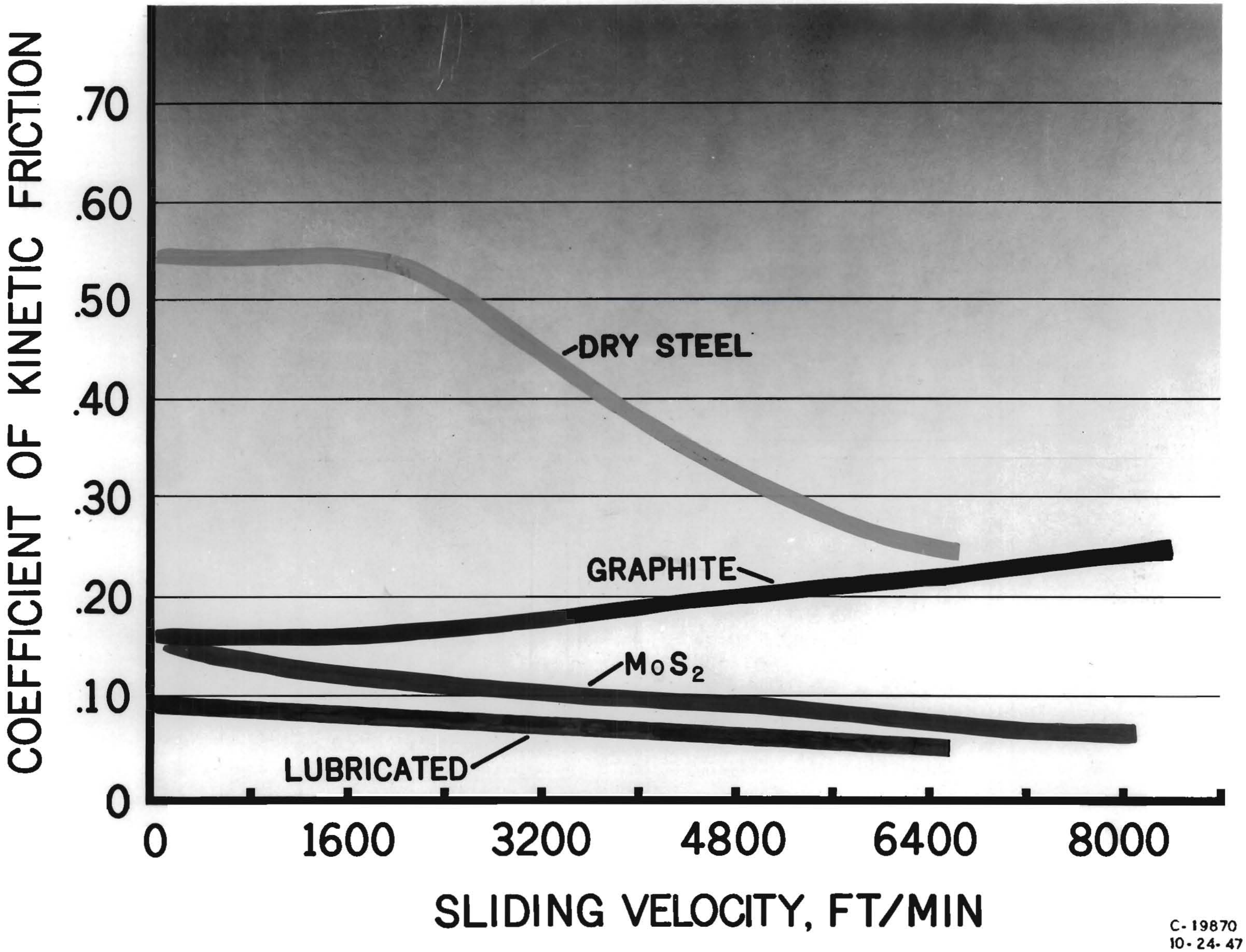
10-24-47

Fig 59

FRICTION AT HIGH SLIDING VELOCITIES

(SOLID LUBRICANTS)



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10- 24- 47

Fig 60

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