TURBINE COOLING

Talk No. 1

Speakers: Henry O. Slone
Jack B. Esgar

In practically all aircraft applications, designers are continually striving to obtain more and more power and at the same time improve engine reliability. Turbine cooling provides a method of obtaining these goals with the gas-turbine engine. In addition, other significant gains in engine performance and engine fabrication are possible due to cooling. In this exhibit, the application of turbine cooling to the turbojet engine will be discussed and a demonstration will bepresented showing the effectiveness of air cooling in a production engine that has been modified as shown in the cut-away model here. The modifications to this engine to accommodate air cooling will be discussed later.

The performance of the gas-turbine engine is limited by the structural strengths of the metals in the hot end of the ending. On this chart (fig. 1) is shown the 1000-hour stress rupture curve for a typical high-temperature alloy currently used for fabrication of gas-turbine blades. The shaded portion above and to the right of the curve represents an area where the material cannot operate safely. For instance,

if the material must operate at a temperature of 1400° F, which is typical for gas-turbine blades, the maximum allowable stress that the material can withstand safely is about 24,000 pounds per square inch. Two methods of increasing the power output in the gas-turbine engine are to use longer turbine blades to permit a larger mass flow through the turbine; or to increase the gas temperature to provide more energy in the jet. Longer turbine blades result in increased stress levels in the metal, and raising the gas temperature means higher metal temperatures. In either case, the limits of the metal strength are exceeded. By cooling the metal, higher stress levels are permissible. This will improve engine reliability, provide a method of increasing power, and permit longer engine life. Cooling also permits the gas temperature to be raised to permit a power increase.

Another important advantage of cooling is shown on the next chart (fig. 2). This curve is the same as on the preceding chart. Now if the metal operating temperature level is decreased to about 1050° F by cooling, a low alloy steel containing only 3 percent strategic material can withstand the same stress level as the uncooled high-temperature alloy containing 97 percent strategic metal. More than half of the alloying content of this high-temperature metal consists of cobalt, columbium, and tungsten, which as will be mentioned in the discussion on materials, are the most critical metals at the present time. The low alloy steel contains no cobalt,

columbium, or tungsten. For the year 1953 it has been announced that 216,000 jet engines are scheduled for production. In order to meet this goal drastic curtailments are required in the quantity of strategic metal used for each engine. Nearly all of the strategic metal is removed from the turbine by use of cooled low alloy steels, and in addition you will note that if the metal temperature is reduced an additional 50° F below the 1050° F previously mentioned, the allowable stress level is more than doubled. This will give a greater degree of freedom in the engine design.

Since the turbine disk and the turbine blades are the most highly stressed parts in the hot end of the engine, they will require the most cooling. The problem then is to obtain a suitable and practical method for cooling these members. Two general methods of cooling gas turbines that have been found to be very effective are air cooling and liquid cooling. Most of our research on cooling of the turbojet engine has been directed towards air cooling. Today's discussion will deal only with this means of cooling. In present gas-turbine practice, more than half of the air that passes through the engine compressor and then through the combustion chambers is not burned. Instead it passes over the outside of this flame tube and then in through these holes to dilute the burning gases and reduce their temperature to the limits imposed by the strengths of the

metals at elevated temperatures in the turbine. The air pressure required for cooling the gas turbine is consderably in excess of ram pressure. A logical solution, therefore, is to take a small part of the high pressure air that has passed through the compressor and use it to cool the structural members in the turbine.

A large number of methods of air cooling have been investigated at the NACA in recent years, and our progress is illustrated on the nextchart (fig. 3). By 1947 the cooling effectiveness of hollow air-cooled blades had been investigated in a static cascade. You will note that this type of cooling requires a large expenditure of cooling air. From a performance standpoint it is desirable to minimize the quantity of air used for cooling, therefore effort was expended to imppove the cooling effectiveness of the blades. The first step was to install an insert in the hollow blade to increase the air velocities through the blade and thereby improve the cooling or heat-transfer rate. Another method of improving the heat transfer from a surface is to increase the heat-transfer surface area. An example of the utilization of increased heat-transfer surface area is the finning found on air-cooled cylinders on the reciprocating engine. This method was used on the finned blade. You may recall that at the last inspection in 1949 the excellent cooling effectiveness of the air-cooled finned blade was demonstrated in a static cascade. Since that time the cooling research has been extended into full-scale engines similar to the

cut-away engine on display. Because of the difficulty in fabricating blades containing a large number of fins in the coolant passage, the first blades investigated in the full-scale engine contained tubes brazed into the coolant passage to provide increased cooling surface area. You will note that the amount of cooling air required for this type of blade was only slightly greater than that required for the finned blade which was considerably more difficult to fabricate. During the period between the investigation on this first tubed blade in the engine and the present time, a large variety of air-cooled blade configurations have been investigated in the engine in order to determine their cooling effectiveness. These blades included finned blades and blades having special methods of cooling the leading and trailing edges. The more promising of the air-cooled blades were endurance tested in full-scale engines operating at rated speed and power. In this way, the blade durability was determined. From this research program, one of the better types of blades that evolves was an improved type of tubed blade shown here. This blade, which has a thinner shell and the tubes extended further into the leading and trailing edges, has the cooling effectiveness of the finned blade shown on the static cascade investigation.

In addition to the good cooling effectiveness obtained with the tube filled blade, the blade is highly desirable from a fabrication standpoint. To demonstrate the simplicity

in its manufacture, I'll start out with this plain hollow tube. By a simple forming operation, this tube can be transformed into a turbine blade shell and the shell can be inserted into a cast or forged blade base. The coolant cavity is packed with a number of small tubes to increase the heat transfer surface area. Brazing powder is poured between the tubes and the blade shell and around the shell at the blade base. The assembly is then inserted into a furnace and the component parts are brazed into a structurally sound turbine blade with a good thermal bond provided between the tubes and the blade shell. After grinding the base serrations and cutting the blade to length, the air-cooled blade is completed and we have a blade that is practical, relatively easy to fabricate, and satisfactory from a cooling standpoint. Mounted here on the backdrop for your inspection later are shown in detail the various steps in the air-cooled blade fabrication method that I have just described.

This is by no means the only air-cooled blade configuration or fabrication method that is practical, but it serves to illustrate one method that has been found to be satisfactory. You will note that this turbine blade is untwisted. It is not necessary from fabrication considerations to make air-cooled blades without twist, however, it has been determined from tests that for some applications untwisted rotor blades used in conjunction with twisted stator blades are satisfactory.

We now have an air-cooled turbine blade for our engine. The next problem is to duct cooling air to it. A method that we have used for our research on turbine cooling is shown on this cut-away of a typical turbojet engine that has been modified to accommodate cooling. The hot end of the engine is illustrated by this sketch and a cross section of the turbine disk is shown here. In this method of cooling the turbine disk was split to provide a central path for the cooling air flow. This split disk arrangement provides a uniform distribution of cooling air along the blade chord and the turbine blades are supported equally by each portion of the disk. The turbine disks are cooled by the same air that is used to cool the blades as it passes between the front and rear faces, consequently the disks are capable of withstanding greatly increased stresslevels. When you consider that the attachment load of each turbine blade may be as much as 12 tons at rated engine speed, the stress carrying capacity of the disks becomes very important. Vanes are used in the disk passage primarily as a distributor and to provide the proper air entrance angles at the blade bases.

Cooling air bled from the compressor is supplied to the turbine wheel through ducts in the tail cone that are insulated from the hot gases by this streamline strut. Sealing of the air as it passes from the tube in the tail cone to the turbine wheel is accomplished by means of a labyrinth seal. The cooling air tube is piloted by means of a spider and bearing arrangement mounted on a shaft that is

supported on the front disk of the turbine wheel. This arrangement assures the proper running clearance between the labyrinth seal and the cooling air tube.

Engines with turbine arrangements similar to that shown by the illustration and by the cut-away engine here before you have been built up and are being used for research here at the NACA. These engines utilize tube-filled air-cooled turbine blades similar to those I have described, and they have been found to have a high cooling effectiveness. The blades can be fabricated by methods that are relatively simple and are readily adaptable to production processes. It has also been found that the method of introducing cooling air to the turbine wheel as shown here on the cut-away is satisfactory. The next speaker will demonstrate the cooling effectiveness of a similar cooled turbine arrangement.

TURBINE COOLING

Talk No. 2

Speakers: Robert R. Ziemer
James E. Hubbartt

In this part of our program we will demonstrate the effectiveness of turbine cooling utilizing blades and a disk similar to those discussed by the previous speaker. The blade temperatures with various amounts of cooling air flow and the disk temperature will be measured in an operating jet engine. This engine, which is similar to the cut-away model displayed here, is set up in one of the test cells along the corridor to your right and is presently running at idling speed. Since the amount of cooling air flowing through the blades will be varied during the demonstration, my talk is being transmitted to the engine operator so that he knows when to make the necessary changes.

For the demonstration we are using the same basic techniques and instrumentation which are used for our experimental investigations. First, I will briefly explain some of the instrumentation required and some of the difficulties involved. The thermocouples, for measuring the blade and disk temperatures, are connected to these temperature indicating instruments on the backdrop. This instrument (point out) will be used for measuring the blade temperature,

this for the gas temperature, and this one for the disk temperature. In this type of installation it is necessary to make a transition from the rotating thermocouple wires from the blades and disk to the stationary wires that are connected to these instruments. This is accomplished by means of a thermocouple pickup which is mounted on the front of the engine. Displayed here is a pickup for six thermocouples which is similar to the one now in the on the operating engine. This pickup was developed here at the NACA. The thermocouple wires pass from the turbine to these slip rings (rotate shaft). The wires from the temperature indicating instruments are connected to these brushes. Thus, when the brushes are in contact with the slip rings, the thermocouples are connected directly to the temperature indicating instruments. The brushes are left in contact with the slip rings for only the short period of time required for reading the temperatures in order to minimize wear. These switches are connected to a solenoid, and when they are on, the brushes are pulled into contact with the slip ring like this (push brushes into contact). During the time that the switch is on, a red light over the appropriate instrument will be on to indicate that we are measuring a temperature. The blade temperature that will be measured is at the midchord position which is indicated by the light on this air-cooled blade profile.

To illustrate the size of the instrumentation being used, here is an air-cooled blade like those installed in the operating engine. A slot has been ground in the shell of this blade for the installation of the thermocouple. This is a typical thermocouple which is encased in a metal tube and bent so that it fits into the slot ground in the blade. After the thermocouple has been located in the slot, like this, it is covered with weld material and the surface is ground smooth. The small thermocouple provides a minimum of disturbance to the heat flow and to the structural strength of the parts. The thermocouple wires, to which these red flags are attached, are slightly larger than a human hair. Because the wires are small, failures are relatively frequent and it is quite possible that a thermocouple may break during the demonstration. However, there are multiple thermocouples at each of the locations at which we want to measure temperatures. These thermocouples are connected to these selector switches. In case a thermocouple fails, I can switch to a good thermocouple located at the same position.

The engine operator will now run the engine up to a higher speed so that we can start our demonstration. An attendant will open the door to the corridor so you can hear the engine being accelerated and you can observe the increase in speed on this tachometer. I want to emphasize that the engine being used for this demonstration is an experimental

engine from which we have already obtained much data and which is currently being used for research. We will therefore run the engine at a speed and gas temperature below rated conditions to conserve our instrumentation.

In the first part of our demonstration we will show how the quantity of cooling air affected the cooled blade temperatures. We will run four points and plot the blade temperatures against coolant flow ratio on this chart. These four points will be for no cooling air followed by cooling-air flow rates which are 1, 3, and 5 percent as much cooling air as gas flow. This is the acceptable coolant flow range for turbojet engines. The cooling-air temperature at the base of the blades is approximately 100° F.

The engine has now reached the speed for the demonstration. No cooling air is flowing through the turbine. We will first read the gas temperature and then the blade temperature. The gas temperature is about 1400° F. The blade temperature is 1420° F. Thus, for no cooling air flow, both the gas and blade temperatures are the same. This gives us the first point on our chart.

The engine operator will now set the cooling-air flow at 1 percent of the total gas flow. When he has set the point, he will press a button which will flash this green light so that we know when to proceed.

The green light is now on so we will again read the gas temperature. It is approximately the same as before. Now

we will see what the cooled blade temperature reads. This temperature is about ____° F. This gives us our second point on our chart. Notice that for the 1 percent coolant flow the blade temperature was substantially reduced by ____° F.

The engine operator is now setting the cooling air flow at 3 percent of the gas flow. There is the light. The gas temperature reads the same as before. The cooled blade temperature now reads ____° F. While the operator is setting the next point, you can observe the shape the curve is now taking. The addition of this 2 percent coolant flow ratio resulted in a smaller temperature reduction in the blade than that obtained by the 1st percent.

The green light has flashed so we can now obtain the fourth and final point on our curve. This is for a 5 percent coolant flow ratio. Again the gas temperature remains unchanged. The cooled blade temperature now reads ____° F. Plotting this point on the curve shows that the addition of the last 2 percent of coolant flow ratio resulted in a smaller decrease in blade temperature than before. This points out the important effect of diminishing returns as the coolant flow is increased. That is, the greatest temperature reductions are obtained by the additions of the initial amounts of cooling air. You will note that at the 3 percent coolant flow ratio the blade temperature has been decreased ____ degrees below tht of the blade with no cooling air. This gives you an indication of the significant gains

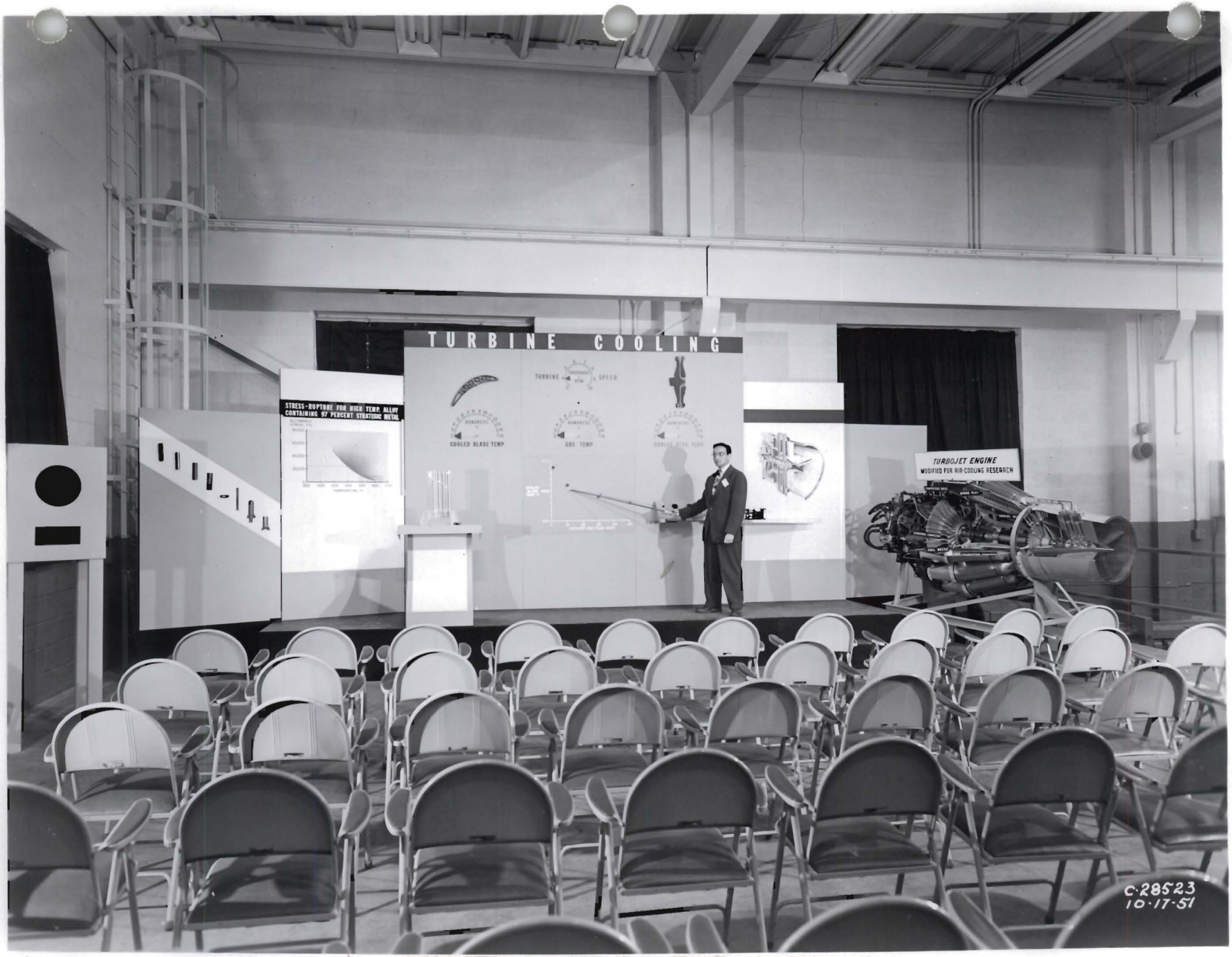
that can be obtained by blade cooling. We are naturally trying to increase the effectiveness of cooling in order to further decrease the amount of cooling air required.

For the second part of our demonstration, we will give you an idea of the operating temperature of an air-cooled turbine disk which is identical to that described by the previous speaker and shown here in the cut-away display model. We cannot show you the variation of the disk temperature with coolant flow ratio because the time required to obtain temperature equilibrium is too long for this demonstration. The disk is cooled by the blade cooling air as it flows from this point of introduction in the rear face to the base of the blades. We will measure the temperature near the rim which is the hottest portion of the disk, and compare it with the gas temperature. Since the engine operator has maintained the conditions which were last set, this will be for a 5 percent coolant flow ratio. The gas temperature is the same as before, about ____ degrees. The disk temperature is ____° F, or about ____ degrees below the gas temperature. If the disk were uncooled, the temperature would be approximately ____° F. The large temperature reduction obtained by cooling will permit the use of low alloy steel disks as well as allow greater disk loading and dependability. The engine operator will now return the engine to idling speed.

To summarize...In the preceding talk, it was explained that if the turbine blades and disk are cooled below present operating temperatures, their strength is appreciably increased, and as a result, an increase in engine power and reliability is made possible. In addition, it was pointed out that if the blades and disk are cooled, they may be fabricated of low alloy steels instead of the scrace high-temperature alloys presently used, and with sufficient cooling their strength will greatly exceed that of present day uncooled turbines. The demonstration that you have just seen represents experimental applications of the cooling principles described by the first speaker and showed temperature reductions which are sufficient for obtaining this additional strength. Due to the success of this and similar investigations, we believe that it is now possible to fabricate cooled turbines from metals which contain only a small amount of strategic materials and to readily adapt them to turbojet engines. The application of this material substitution, along with adequate cooling, will facilitate engine production and eventually make increased engine power possible. The results of our cooling research is being disseminated to industry by means of reports and frequent conferences. Industry is working along with us in the application of these results.

This concludes our program on turbine cooling. Please feel free to come up and see our display here on the platform.

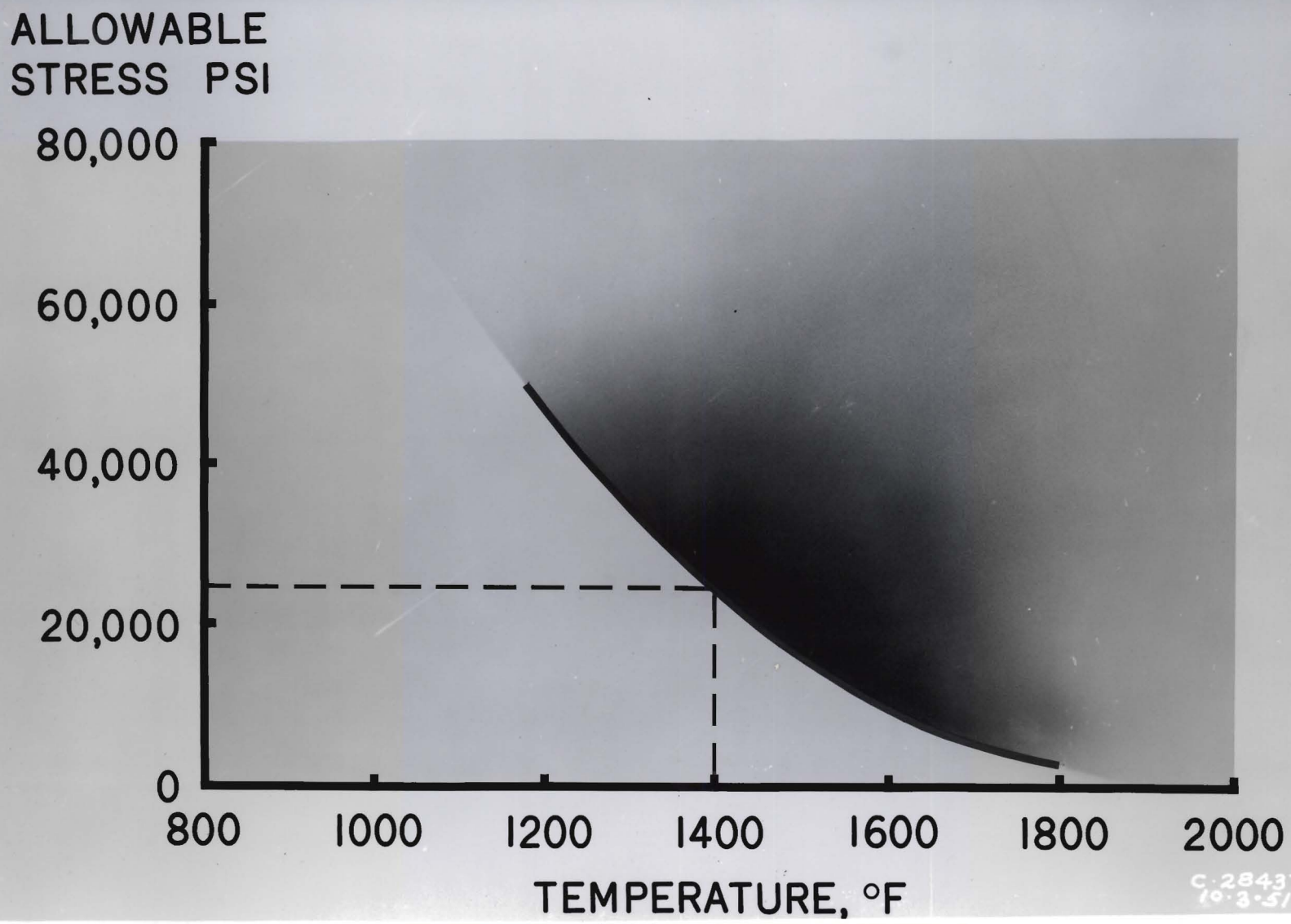
The group leader will take you down the corridor to your right, where you will see an air-cooled jet engine, similar to the one operated for the demonstration. The demonstration engine will be hear d running at idle conditions in an adjoining cell. Thank you.



Setup -- Turbine Cooling Demonstration

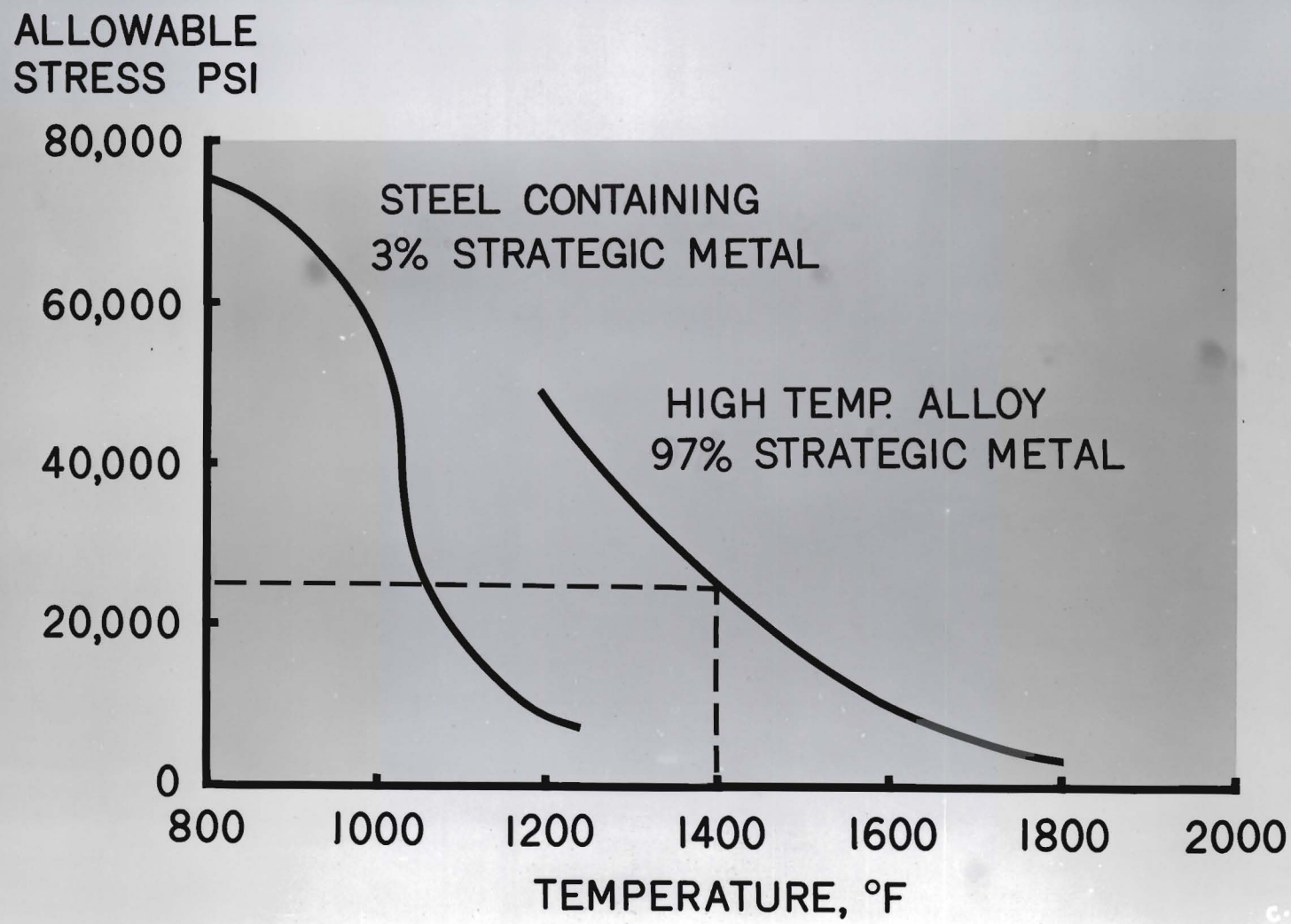
NACA

STRESS-RUPTURE FOR HIGH TEMP. ALLOY CONTAINING 97 PERCENT STRATEGIC METAL

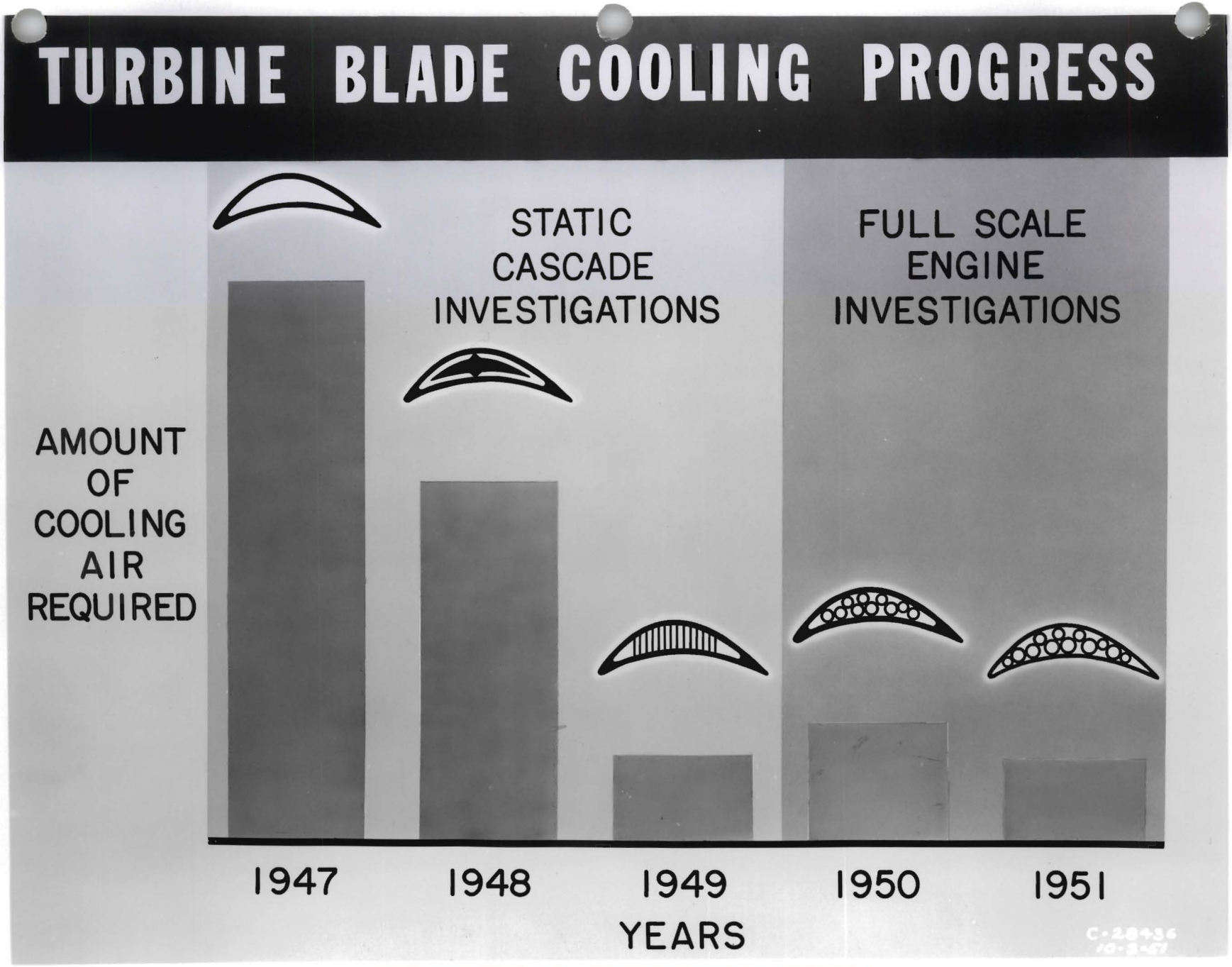


Turbine Cooling -- Figure 1

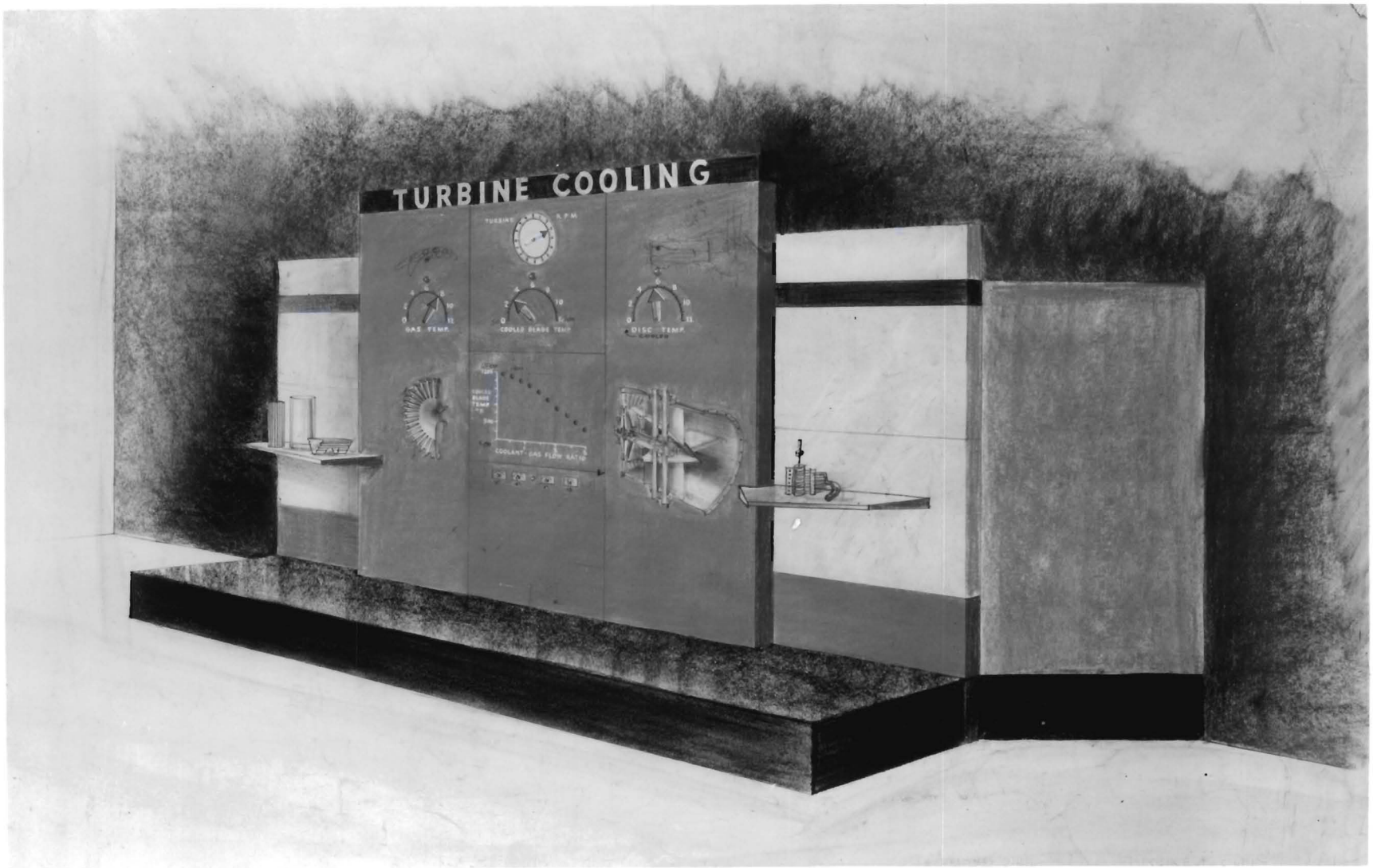
STRESS RUPTURE FOR STRATEGIC AND NON-STRATEGIC METAL ALLOYS



Turbine Cooling -- Figure 2



Turbine Cooling -- Figure 3


TURBINE COOLING
TURBINE R.P.M.
GAS TEMP.
COOLED BLADE TEMP.
DISC TEMP.
COOLANT GAS FLOW RATIO

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