AIRBREATHING ENGINES

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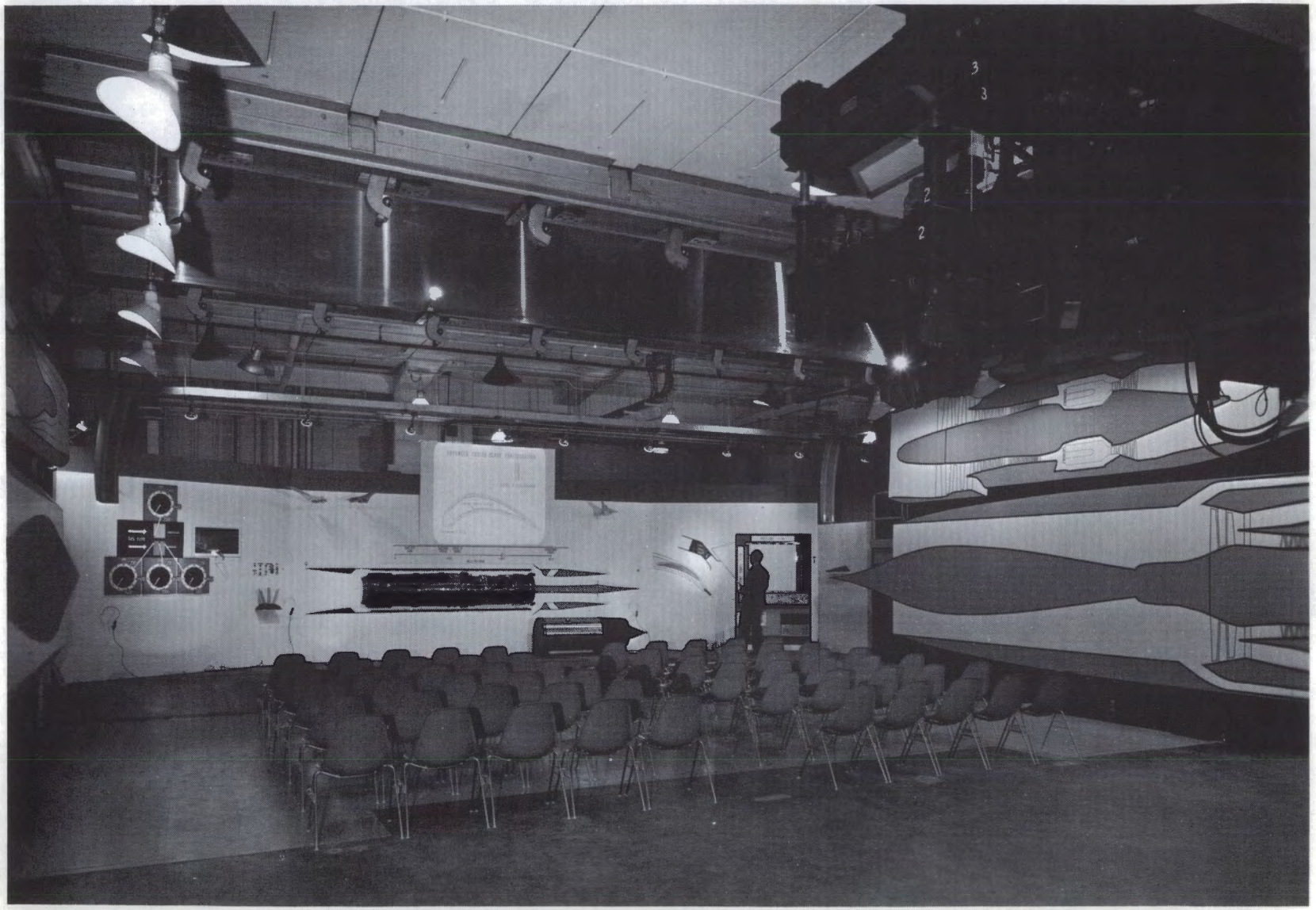

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INTRODUCTION

Aircraft now under development will have capabilities that greatly exceed those of current aircraft. For example, future fixed-wing aircraft will take off and land vertically. Other aircraft will cruise on-station for long periods of time and will fly great distances with big payloads. Large aircraft like the B-70 and the supersonic transport will cruise three times as fast as present airline jets, yet take off and land at speeds comparable to these jets. These new aircraft will require improvements in engine design to provide greater thrust per pound of engine while still maintaining good fuel economy, operational flexibility, and high reliability.

Lewis Research Center is supporting this engine improvement effort through in-house research and contracts with the aerospace industry. It is our purpose today to acquaint you with the character of this work by discussing a few aspects of this highly diverse field. We will begin our discussion by reviewing the essential components of a turbojet engine.

A complete turbojet engine system consists of an air inlet, an air compressor, a burner in which heat is added to the compressed air, a gas turbine through which the hot compressed gas is expanded partially to drive the compressor, and a nozzle to complete the expansion of the gas and accelerate it rearward at high velocities. Thrust is produced when the velocity of the gas leaving the nozzle exceeds the velocity of the air entering the inlet. The greater the difference in these velocities, the higher the thrust. On some turbojet engines, by using an afterburner behind the turbine to add additional heat, as shown on the lower engine schematic, important gains in thrust are obtained.

Here on your right is illustrated a variation of the jet engine, called the turbofan. In this engine the blades on the first two stages of the compressor are increased in length to provide the equivalent of ducted propellers. These enlarged blade stages are called a fan. This is an example of one of these fan blades. The air near the hub of the fan passes through the main engine compressor. The remainder of the fan airflow bypasses the main engine compressor and turbine. At times in the flight of some airplanes, it is desirable to burn some fuel in the bypass air for extra thrust. This is accomplished in the "duct burner" shown in this engine.

The larger engine schematics on your right and left are full-scale for the proposed supersonic transport which is commonly known as the SST. Their counterpart is a full-scale schematic. Above each of the proposed SST engines is a full-scale schematic of their counterparts used in today's subsonic jet transport. The thrust of these current engines is about one-fourth that of the SST engines. Referring to the schematics at your left, you can see that, in addition to size, the principal difference between engines for subsonic and supersonic flight is the larger proportion of the engine system that must be devoted to the inlet and the nozzle for supersonic flight.

Today, we will discuss special problems of the inlet and nozzle for aircraft, such as the F-111, the B-70, and the SST, which fly between two and three times the speed of sound. Also, our discussion will cover an approach to compressor blade design that may give important reductions in the size and weight of this heavy engine component. Finally, we will discuss a type of air-cooled turbine blade for use at the higher engine operating temperatures that are required to derive more thrust from an engine of a given size.

INLET AND EXHAUST NOZZLE STUDIES

Let us start our review of NASA aircraft engine research by considering the novel problems associated with this large supersonic inlet. This inlet must do two jobs. First, it must take in the proper amount of air to satisfy the engine airflow requirements. Second, it must slow this air to low subsonic speeds that are acceptable to the compressor, and, in doing so, convert the high kinetic energy of the incoming air to air compression. The inlet must accomplish these jobs efficiently over a range of flight speeds from takeoff to twice the speed of sound and higher. Generally, the inlet is sized to accept the quantity of air required by the engine at supersonic cruise. At other flight speeds, the shape of the inlet must change to maintain the proper match between inlet air supply and engine air demands.

We are going to use this semischematic propulsion system to illustrate the required shape changes of the inlet during a simulated supersonic flight. You will recognize the inlet from the illustration on the side. In three dimensions, it would look like this. The cutaway shows the compressor, burner, and turbine. The matching problem of the inlet has its counterpart in the nozzle and we will discuss this as we go through the flight.

The scale above the engine will indicate the flight speed. The changes in shape which you will see have been synchronized with the flight speed shown. At takeoff, the inlet does not admit enough air to meet the engine demand and therefore these small doors are opened to admit the extra air. Now we will begin the flight. Shortly after takeoff, the airplane speeds up, and as the inlet captures enough air to meet engine demand, the auxiliary doors close. At low speeds, the engine exhaust flow is not sufficient to properly fill the nozzle. This results in loss of thrust; therefore auxiliary doors are open to scoop additional air. Notice also that the trailing flaps are tipped inward to form a converging passage. This is the nozzle configuration for all subsonic speeds.

As the airplane passes through the speed of sound and accelerates to supersonic speeds, more air is ingested by the inlet than is required by the engine so the inlet bypass is opened to spill the surplus air.

At this phase in the flight the exhaust flow fills the nozzle and additional air is no longer required, so the auxiliary doors have closed. To maintain full expansion of the engine exhaust, the trailing flaps have opened to form a diverging passage to provide full expansion of the exhaust flow to give maximum thrust.

By the time a flight speed of 1200 miles per hour is reached, all the nozzle variations will be completed, and the shape of another part of the inlet will begin to change to maintain efficient compression and to slow the air. As the speed is increased to cruise, 1800 miles per hour, the inlet bypass will gradually close and the inlet centerbody will expand.

The operation of the inlet and nozzle must be coordinated with the other components of the engine by means of a control system which senses airplane flight speed, altitude, engine airflow and fuel flow, and sets the inlet and nozzle accordingly. The pilot will only operate the simple fuel throttle that he uses on present airplanes.

Here at Lewis we are doing research on inlets and nozzles and control systems which are required for accurate positioning of the moving parts of these components.

COMPRESSOR DEVELOPMENT

The elaborate inlet and nozzle have added undesirable weight to the engine. This should be compensated by weight reduction of other engine components, particularly the air compressor, since it is one of the heaviest engine parts as you can see on these engine illustrations. Our discussion of one interesting scheme being studied at Lewis for reducing compressor weight begins with a brief description of the com-

pressor. This compressor is made up of alternate rows of rotating and stationary blades. One rotor and stator blade together constitute rows and is called a stage. This compressor has eight stages. For economical engine operations, it is essential that this air compression be done very efficiently. The compression that can be done in one stage, efficiently, is limited. Therefore, multiple stages are required to achieve the necessary compression. If we could increase the compression in each stage - and maintain efficient performance - we could reduce the number of stages and reduce the size and weight of a large and heavy engine component.

To describe why the compression per stage is limited, let's review the nature of flow through a compressor blade row. In this model of a segment of such a blade, air flows through the blading in this manner. An endview of these blades is shown on the left on the first slide (fig. 1). Air enters the blade row here, as shown by the arrows, is deflected by the blading, and is discharged here.

This type of blading is used in current engines. The blades have a moderate amount of curvature which produces a modest deflection of the air. It is this deflection of the air by the blades that is the key factor in compressing the air - the greater the deflection, the greater the compression.

Therefore, in order to increase the compression per stage, the shape of the blades must be changed to cause more deflection. On the right is a compressor blade designed for higher compression. This blade has more curvature which increases the deflection of the air flowing through the blade row as indicated by the arrows. If this type of blading could be used in a compressor, it would result in fewer stages.

Unfortunately, there is a limit to the amount of blade curvature that can be used efficiently. This is illustrated on this model blade. The airflow approaches the blade as shown by this arrow. Here the curvature is too large for the flow to follow and a separated or dead

air region develops on the convex surface of the blade. The desired deflection of the flow is not achieved. Low compression and large losses in efficiency accompany this poor flow. We can detect this separated flow region by making a pressure survey behind the blade.

We are going to conduct such a pressure survey in this apparatus. You can see three high-deflection compressor blades. They are mounted in a flow duct behind the panel. Air enters the duct about here and flows to your left over the blades. A pressure-measuring probe will be moved across the airstream behind the center blade. The pressure it measures will be displayed on this automatic plotter. As the probe moves across the airstream, the pen will move up the chart. The pressure measured by the probe will be indicated by horizontal movements of the pen. High pressure here, low pressure, here. Watch these tufts as I turn on the air. Now I will start the probe moving.

The probe is between the blades and the pressure is uniform and high. Now the probe is in the separated flow, and the pressure has dropped. The waviness of the trace indicates the unsteady character of the separated flow. (As the probe moves out of the separated flow region, the pressure returns to its between-blade values -- <u>if this happens</u>.)

This large area of low pressure shows that the efficiency of these blades is unacceptable.

However, we would like to use these high-deflection blades which give more pressure rise per stage, if we could prevent the disastrous flow separation which you have just seen. We are presently exploring ways to accomplish this. For example, the compressor blade may be made with a slot such as the one on this model. These streamlines indicate how flow through a correctly placed slot will replace most of the dead air slowed by friction on the convex surface with highly energetic air drawn from the concave side of the blade. Most of the undesirable flow separation is thus avoided.

We can demonstrate the effectiveness of this slot by moving a set of blades into the airstream that are identical to the ones just tested - except that they are slotted - like the model. We have colored the tips of these blades red and green to make the slot more evident. We will survey the pressure behind the center blade again and superimpose the result on the one for the solid blade.

The probe is now in the separated region of the slotted blade. A comparison of the low-pressure areas shows that the slot has reduced separation and pressure losses to acceptable levels for high-performance compressors. We are studying slotted blades and other schemes in order to achieve the compact, lightweight compressor.

TURBINE COOLING RESEARCH

Another critical engine component is the turbine. To increase engine thrust without increasing engine size, it is desirable to raise the temperature of the gas at the inlet to the turbine. However, the level of turbine inlet temperature is limited by the low strength of blade materials at high temperature. This bar graph (fig. 2) of turbine inlet temperature shows that current commercial engines cruise at temperatures of about 1400° F and climb for short periods at about 1600° F. These temperature levels are set by current materials limitations. Advance engines, such as the SST engine, will have to cruise and climb at turbine inlet temperatures that exceed 2000° F. Potential improvements in materials will provide some of this required increase in turbine inlet gas temperature. But the rest of this increase must be accomplished by cooling the turbine to maintain turbine blade temperatures below this level. Some military engines using cooled turbines already operate at these higher temperature levels, but these engines have comparatively short operating lives. For the long life required of engines for commercial transports,

appreciable improvements in turbine cooling techniques will be necessary.

Turbine cooling is not a new idea. NASA and its predecessor, NACA, did pioneering work in turbine cooling dating back to 1947, and many present cooling schemes are based on this early work. The principle of turbine cooling can be explained with the figure on your left. In an air-cooled turbine, relatively cool air from the compressor is bypassed around the burner and routed through internal passages in both the rotating and stationary blades to cool them. This cooling air must lower the blade temperatures to levels where material strength is adequate and maintain an even temperature throughout the blade to avoid severe thermal stresses.

Here in my hand is an air-cooled turbine blade. You can see a hole in the base of the blade through which the cooling air is admitted.

Recent advances in heat-transfer analysis and blade fabrication techniques have made it possible to build blades with highly effective cooling schemes. The next slide (fig. 3) illustrates an air-cooled blade that is currently being investigated here at Lewis. It shows the elaborate cooling arrangements that we can build into our turbine blades now. The outer shell of the blade forms the aerodynamic profile that is acted on by the hot gas stream. This is the part of the blade that must be cooled. The hot gas flow approaches the blade in this direction. Cooling air is supplied from this center section of the blade. At the leading edge, where the heat input to the blade shell is the highest, multiple jets of cooling air impinge on the inner surface to increase the cooling rate. This cooling air then exits through these slots to form a film or jacket of cool air which protects the shell from the hot gas stream. The rest of the blade is convectively cooled by the air flowing through small passages formed by fins in the blade shell. This cooling air then discharges through trailing-edge slots into the gas stream. By carefully controlling the cooling rates in the various parts of the blade, we avoid high temperature gradients and the undesirable thermal stresses.

To illustrate the effectiveness of this cooling scheme, we have prepared a demonstration using this type of air-cooled blade and an uncooled blade in the same hot gas stream. Through this window you can see these two blades mounted tip-to-tip behind a burner, as shown on this enlarged illustration with the uncooled blade on the top and the cooled blade below. Thermocouples at these locations will indicate the blade temperatures on these dials which are graduated in hundreds of degrees Fahrenheit - thus a reading of 16 will mean 1600^{o} F.

When we start the demonstration, you will notice that the uncooled blade will assume a bright yellow color as its temperature rises rapidly to about 1900^{o} F.- approximately here on the dial. Meanwhile, the color of the cooled blade will become dull red as the temperatures rise more slowly to an even level of about 1300^{o} to 1400^{o} F - approximately here on these dials.

We will now begin the demonstration.

We have demonstrated one kind of air-cooling scheme for turbine blades. NASA foresees a long term program in turbine cooling research to keep pace with the projected use of still higher turbine inlet temperatures in future engines.

F-106 FLIGHT TEST PROGRAM

NASA research and development program for advanced engines includes the problems of all the engine components, some of which we discussed, the matching of these components to form an integrated propulsion system, and the mating of this system with the airplane. One of our main facilities for studying the difficult problem of integration of engine components into a complete propulsion system is the 10- by 10-Foot Supersonic Wind Tunnel. The floor of this tunnel is mounted on an elevator. It has been lowered and you are sitting

on it. Flight speeds to $5\frac{1}{2}$ times the speed of sound can be simulated here. The test section is above your head where you can see a small jet engine complete with inlet, nozzle, and experimental control system all arranged for supersonic operation. During some of the studies with this setup the trapezoidal plate ahead of the inlet will oscillate rapidly to produce simulated atmospheric turbulence in the air entering the engine.

Because the airflow through and around the engine reacts with the airflow around the airplane in flight, we tailor the engine design and its location on the airplane to get the best engine-airplane combination. Such studies are made with carefully designed models in wind tunnels such as this. Companion studies are conducted in airplane flight. Presently, for example, we are planning to mount the same propulsion system shown in the tunnel on a F-106. The airplane with test engine mounted will look like this model. The F-106 was chosen because its shape is similar to many supersonic airplanes such as these.

CONCLUSION

While our discussion has been directed primarily toward engines for supersonic flight, much of the information we seek in this area applies to advanced engines for subsonic flight as well as lift- and lift-cruise engines for vertical takeoff and landing. These other engine types will be subjected to the same detailed studies that we have been discussing.

As you proceed to your next stop, you will pass several jet engine displays, including full-scale mockups of the engines proposed for the SST.

(IF DEMONSTRATION DOES NOT WORK)

Our permissive control circuit is indicating that there is an unsafe condition somewhere in the system; thus we cannot establish ignition to give you a live demonstration. As a substitute, we will refer to this color transparency of a photograph that was made of these blades during a previous test run. The orientation of blades in this transparency is the same as seen in the window and on the enlarged illustration. During this previous run, the uncooled blade temperature settled out at 1900^{o} F and the temperatures on the cooled blade were 1300^{o}, 1300^{o}, and 1400^{o} F at these locations. The bright color on the uncooled blade and the dull red color on the cooled blade are characteristic of these temperature levels.

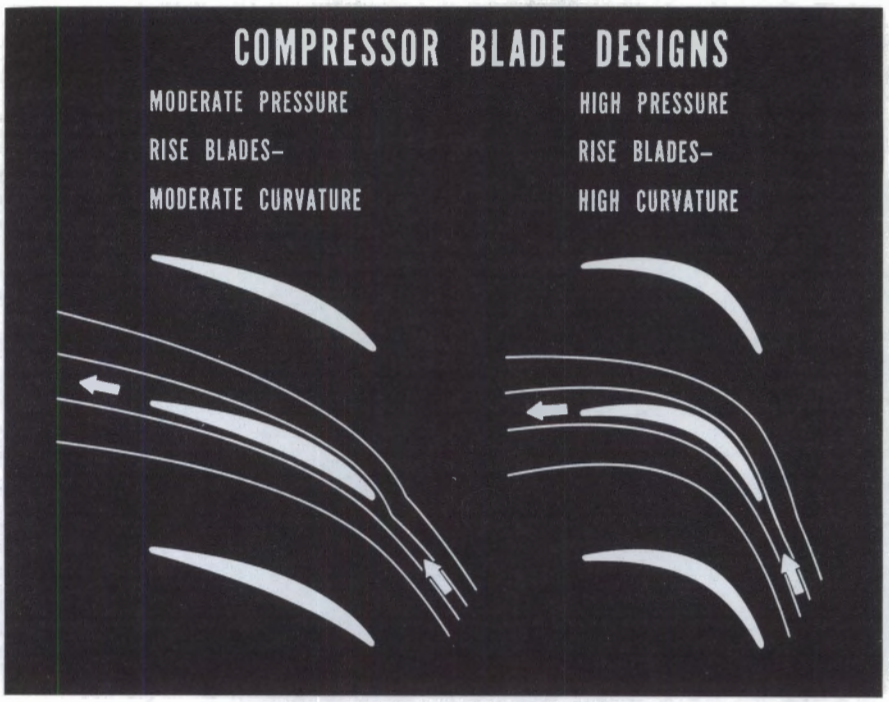

Figure 1

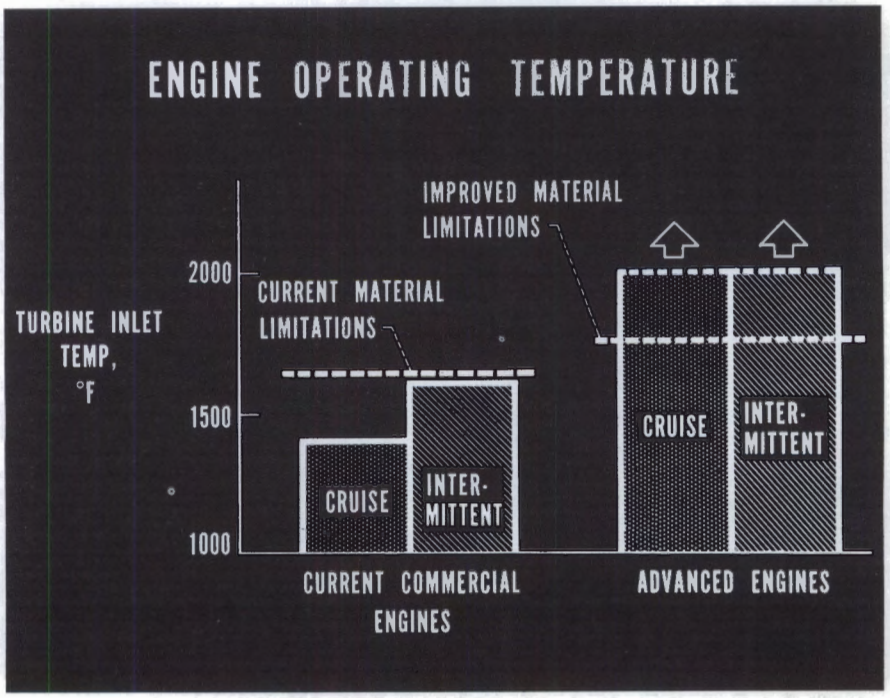

Figure 2

ADVANCED COOLED-BLADE CONFIGURATION

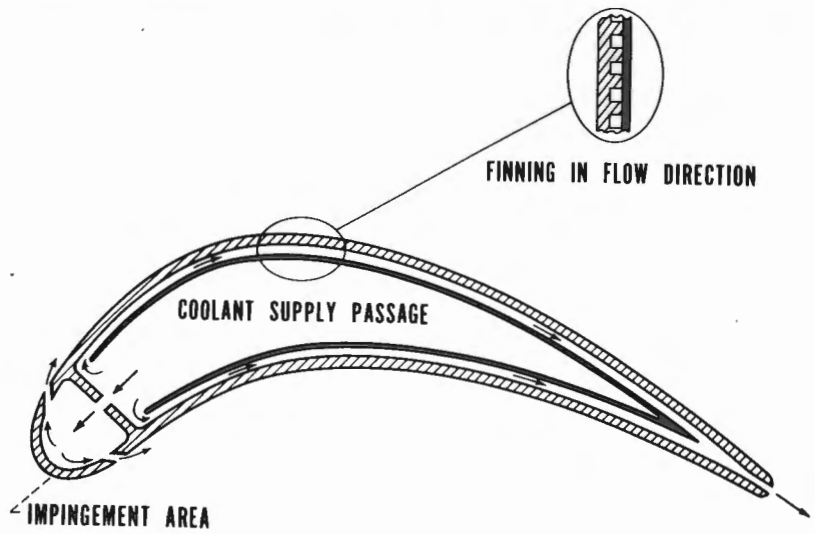

Figure 3

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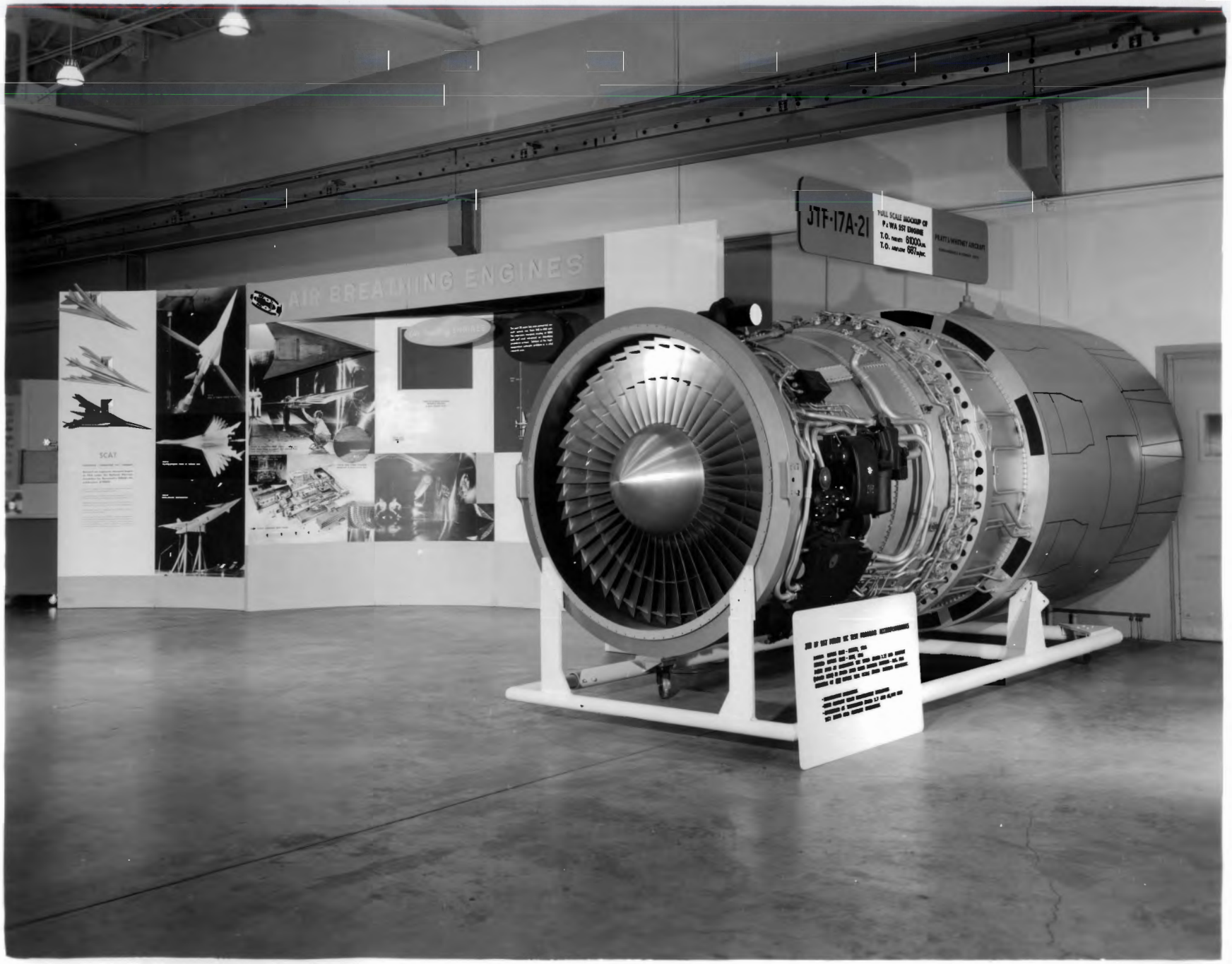

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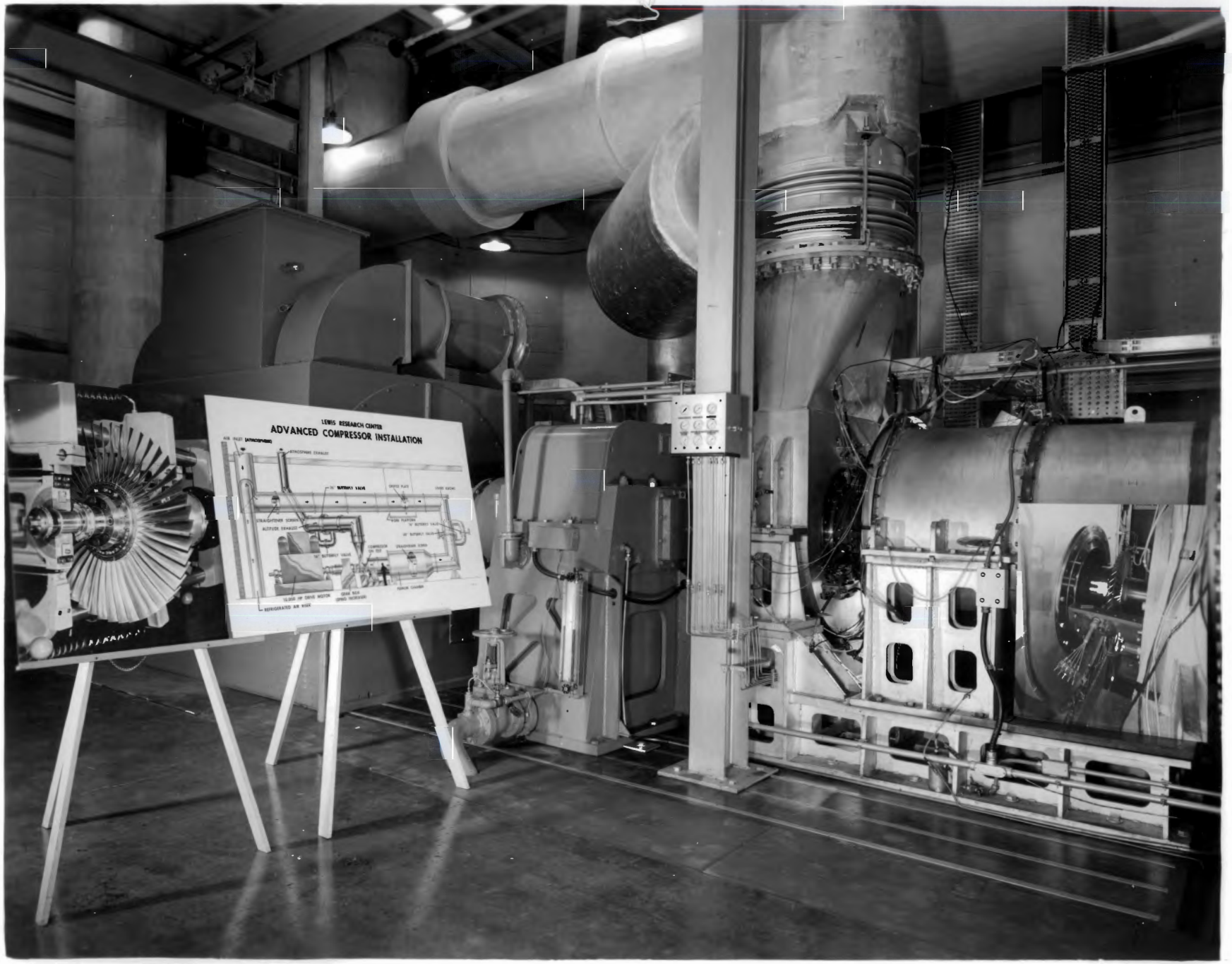

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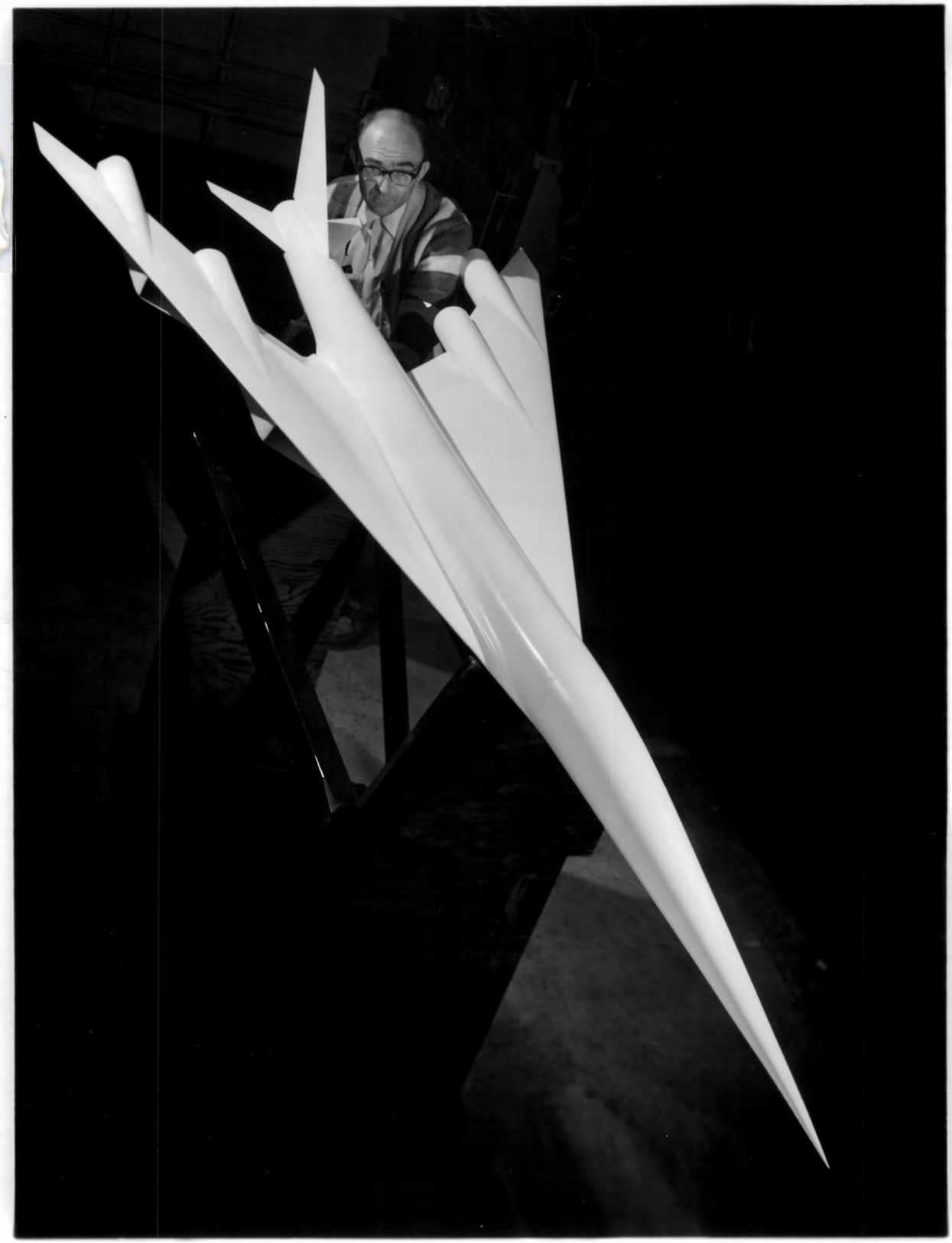

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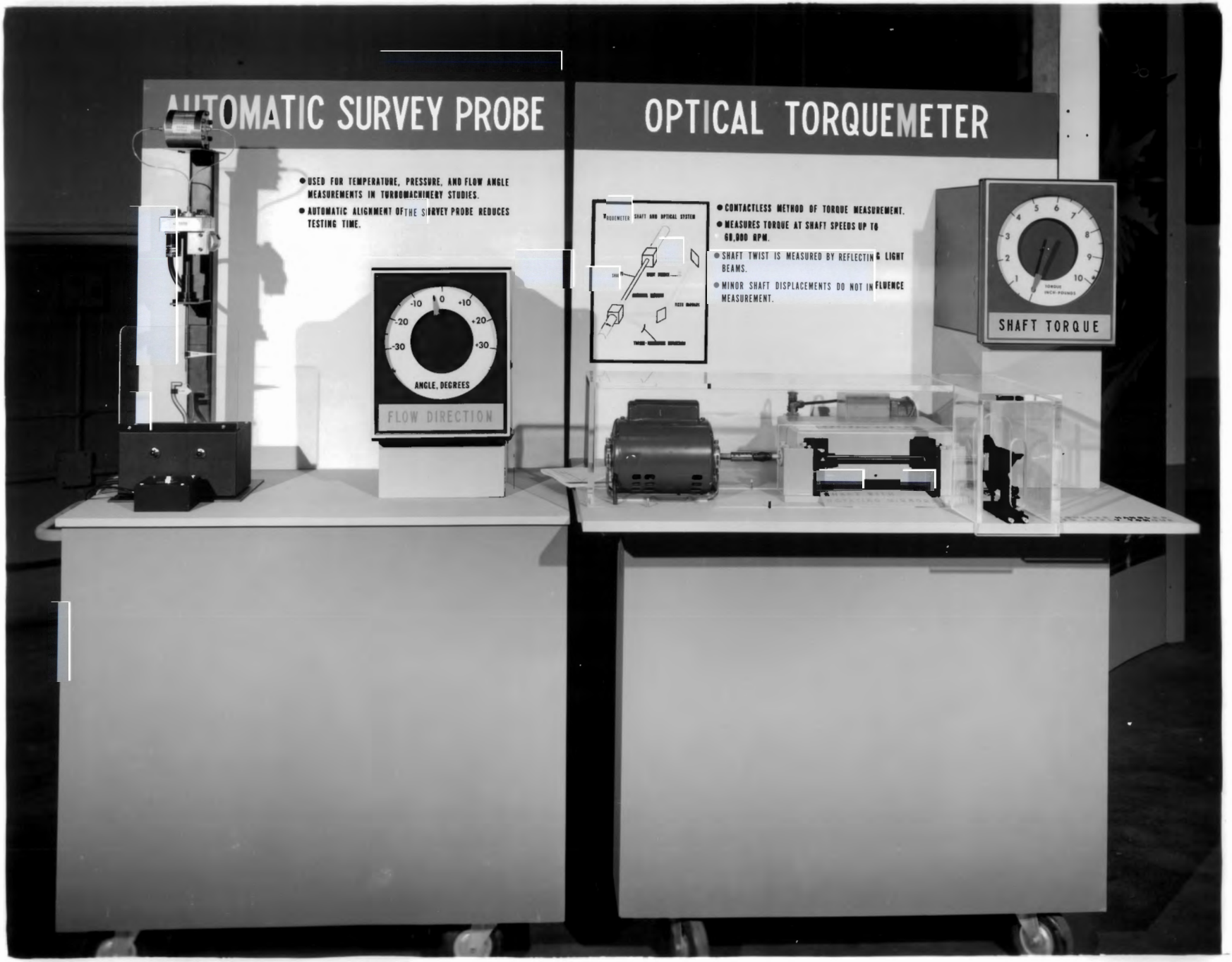

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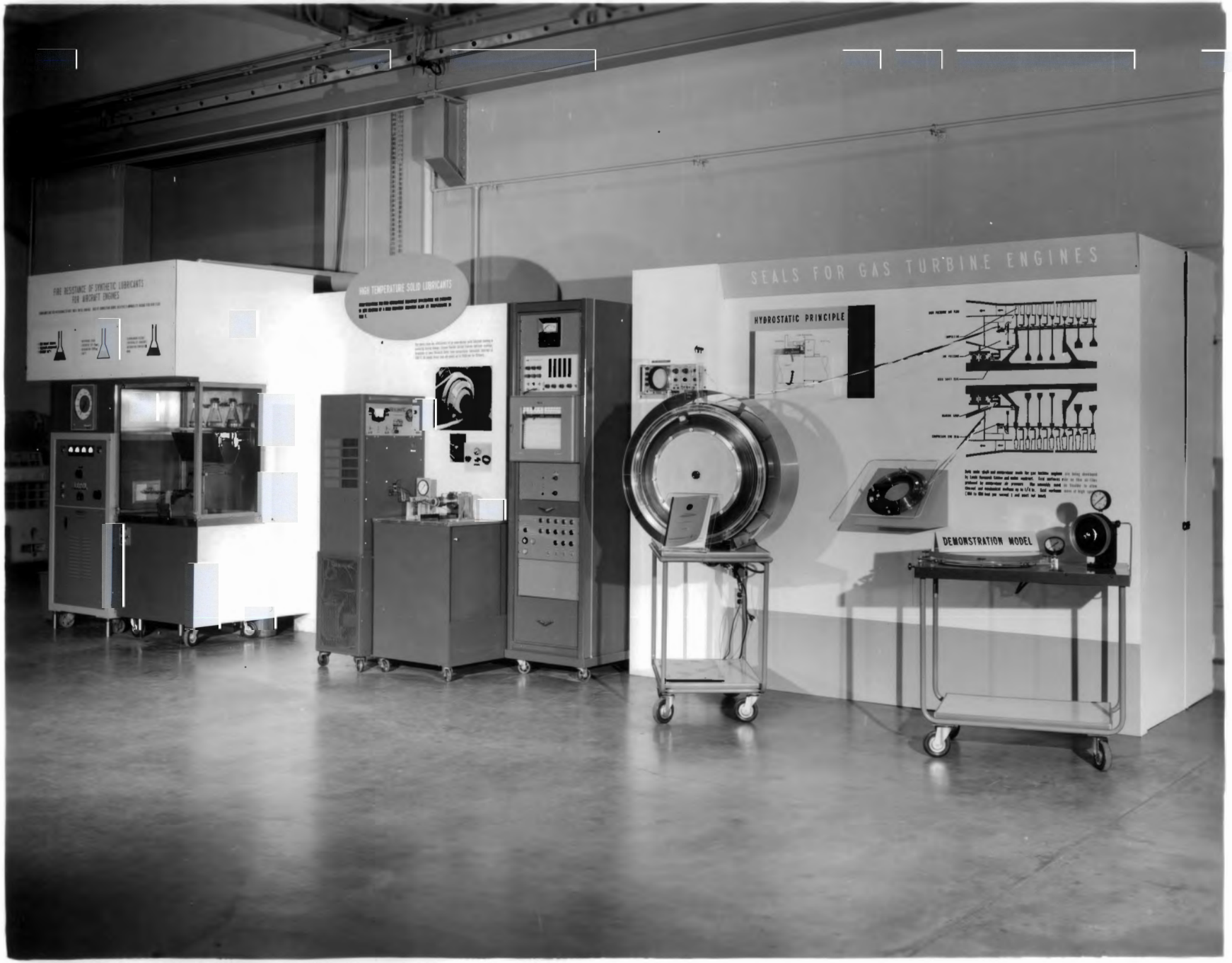

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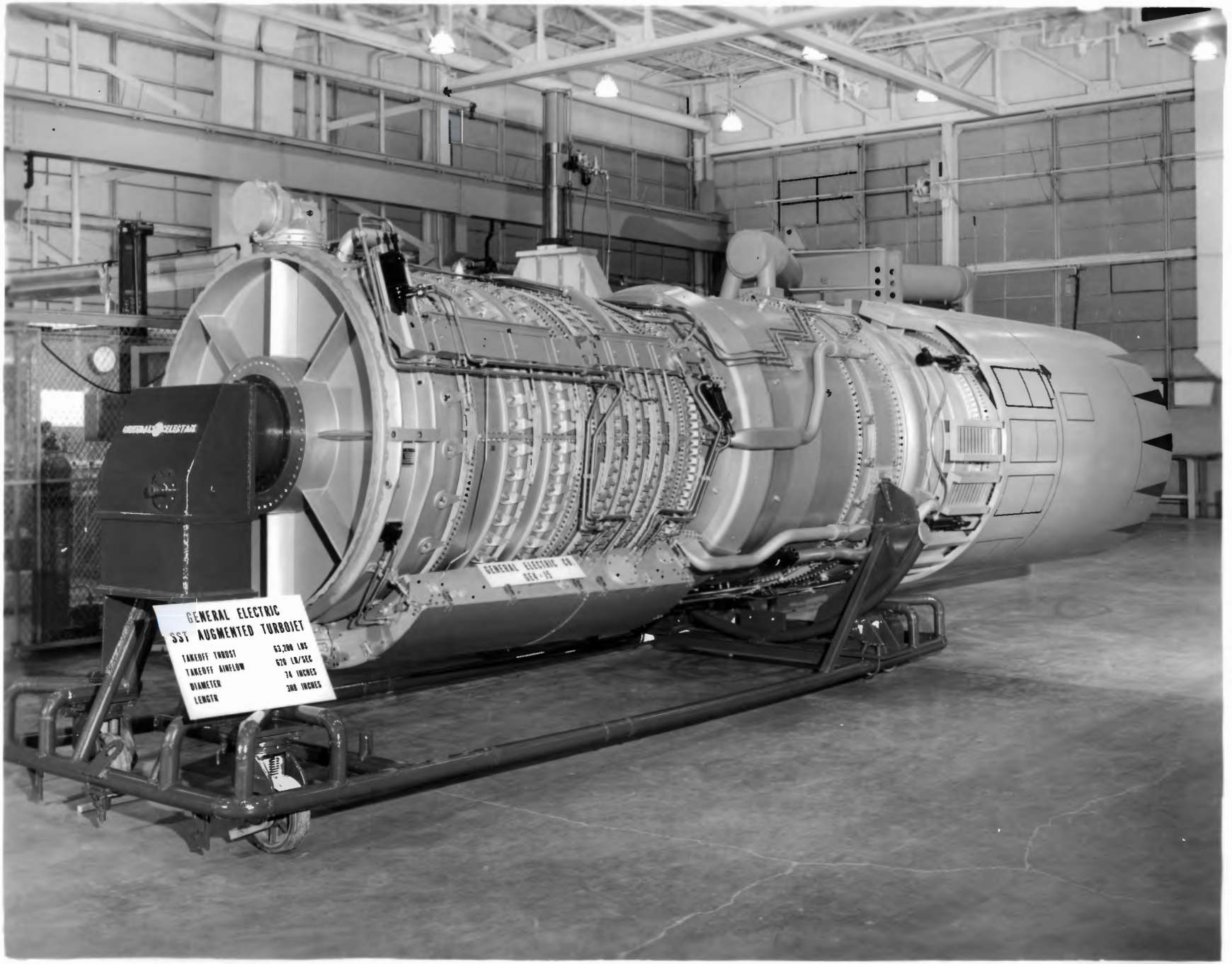
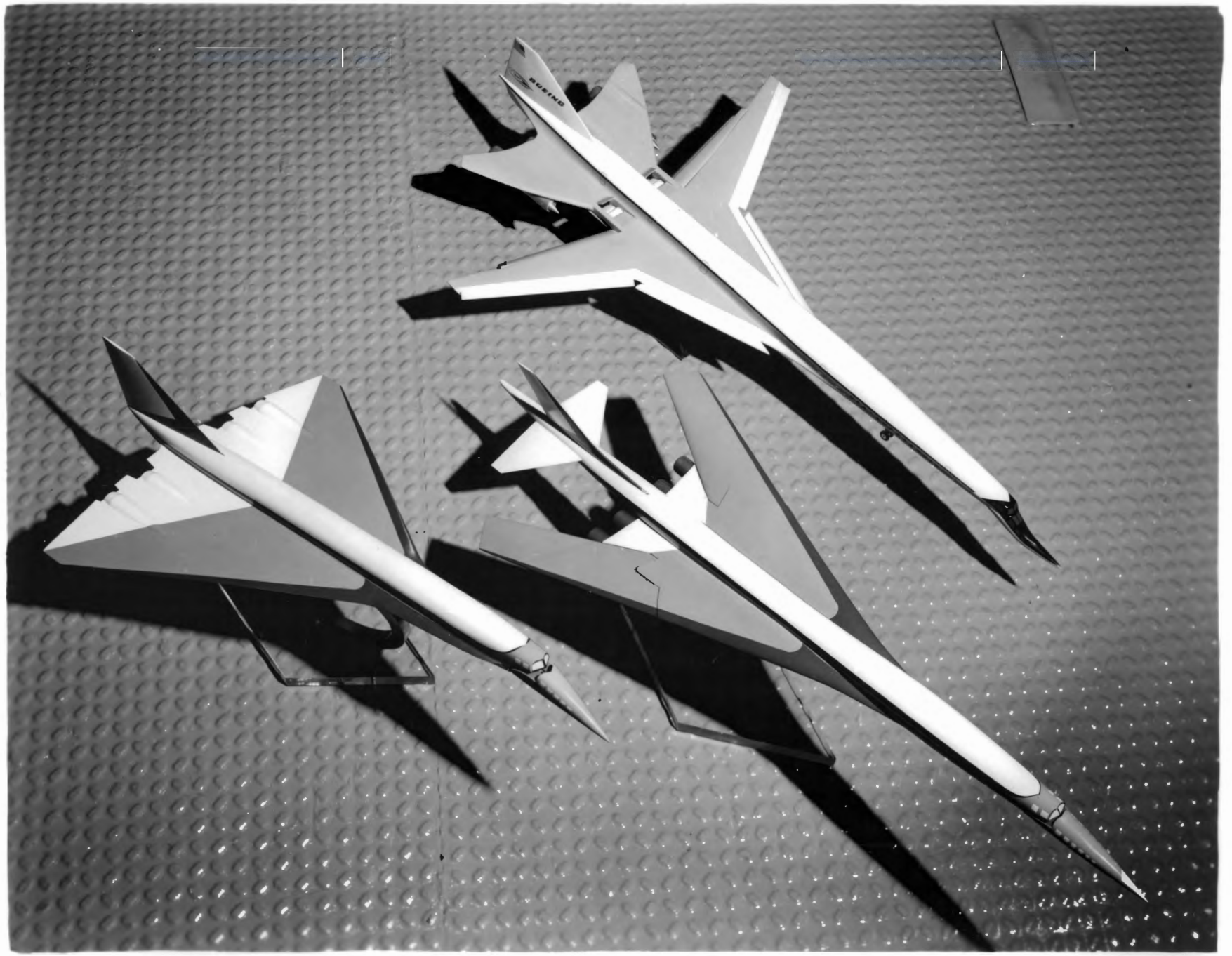
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