COMPRESSOR RESEARCH

Part I - Advanced Compressor Design

by Harold B. Finger and Robert E. English

The engine research work of the NACA is directed toward the objective of developing as much thrust or power as possible in as small and light an engine as possible without sacrificing the engine efficiency.

For example, let us look at this turbojet engine (right, off stage) which is one of those now being used in some of our airplanes. Here is the compressor component of the engine in which work is done on the air. We have raised the compressor casing so that you can clearly see the rotor and stator blades of the unit. Here is the burner section in which the air temperature is increased through the addition and burning of fuel; and here is the turbine which is directly coupled to the compressor and supplies the power for driving the compressor. The principal methods of getting as much thrust as possible out of such an engine are, first, to increase the air temperature at the inlet of the turbine rotor and, second, to increase the amount of air flow that can be crammed through the engine. In past years, we have talked about the large gains in thrust that can be achieved by the use of turbine cooling to permit higher turbine inlet temperatures. This year, at this exhibit, we will discuss the methods that are available for increasing the amount of air that the compressor can deliver to the other components of the engine without changing the outside dimensions of the unit. In addition, we will talk about possible means of reducing the weight of the engine by reduction in compressor weight.

In the first chart (C-35915), I have shown the methods for increasing air flow through the compressor. Here, I have plotted the air flow as a percentage of the maximum possible flow. This maximum air flow is the amount of flow that can be passed through an open pipe. On this scale, I have the Mach number of the air entering the compressor. The Mach number is defined as the ratio of the air speed to the speed of sound. In other words, you might consider that this scale represents simply the speed of the air into the compressor. Each of these lines represents a different ratio of hub-to-tip diameter for the compressor. It is immediately apparent from the chart that the smaller the hub-tip ratio, the more flow we can pass through the compressor for a given tip diameter. These three hub-tip ratios are illustrated by the three compressors shown on the chart and, better still, by these three single-stage compressor wheels mounted on this panel. You can see that the smaller the hub-tip ratio, the longer the blades. This increased blade length explains the increased flow capacity. In addition, the chart presents a curve for an 0.3 hub-tip radius ratio which would have even a smaller hub diameter and longer blades than these of the 0.5 hub-tip ratio wheel. In addition to increasing the flow by reducing the hub-to-tip ratio, we could get more flow, and therefore more thrust, for any one of these wheels if we could increase the Mach number or the air speed entering the compressor.

As I mentioned earlier, the second part of our objective is aimed at reducing engine weight. Let us again look at this current engine. You can see that the weight of the compressor component of the engine is determined principally by the large number of blade rows in the unit. Therefore, one way of reducing the weight of the engine is to reduce the number of blade rows required. This requires that each blade row do as much work as possible.

The next chart (C-35912) indicates the means available for increasing the pressure rise, which is equivalent to the work, of each blade row. On this scale, I have plotted the pressure rise across the stage. On this lower scale, we have the Mach number relative to the tip of the rotor row. This relative Mach number represents the air speed that you would see if you sat on the rotor blade as it turned. The two lines on the curve represent blade speeds of 1000 and 1400 feet per second. It is apparent from this curve that we could get more pressure rise or work out of each stage in the machine if we could run the rotor at a higher speed. In addition, we could get higher pressure rise at any given speed by increasing the Mach number relative to the rotor row.

Our theoretical analysis has thus indicated several things that might be done to increase the air flow through compressors of a given size and to decrease the number of blade rows in compressors. In general, these changes require use of air speeds and blade speeds which are higher than the speeds commonly used. Our current compressors have not made use of these higher air and blade speeds because of the losses in efficiency that resulted.

The problem, therefore, is to obtain these increased blade speeds and air speeds in our compressors without sacrificing efficiency. From this large scale model of a compressor blade (lower left of stage), you can see that the blade is actually designed as a series of airfoils (similar to an airplane wing) stacked one on top of the other. For conventional airfoil shapes such as this one, we find that if we increase the air velocity ahead of the blade to values near the speed of sound, large losses in efficiency result. The manner in which these losses arise is shown in the following movie. (Langley supersonic tunnel sequence)

Here is a conventional airfoil mounted in an air stream. Air entering here at a subsonic velocity passes over the air foil. The velocity of the entering air is indicated on this dial. At the present time, the inlet velocity is already up to 72 percent of the speed of sound. This dark region contains air which is rapidly accelerating near the nose of the airfoil. You can see that a shock wave has developed on the upper surface of the airfoil. The air passing through this shock waves undergoes a sudden, abrupt pressure rise. The presence of this shock wave indicates that the velocities in this region are supersonic even though the inlet velocity is less than the speed of sound. Downstream of the shock wave, you can see a light layer on the upper surface of the airfoil. This region contains air that has undergone an energy loss. The thicker this region, the higher the loss in energy of the air flowing over the airfoil. It is apparent now that as the air velocity is continually increased from the original value of 72 percent of the speed of sound, this loss region thickens and the shock wave becomes more and more pronounced. Thus, as air speed is increased above about 0.7 for conventional airfoil sections such as this one, the losses increase and the efficiency decreases. (Movie off)

Although we have discussed the performance of a single airfoil, a very similar effect has been found in compressors. For example, this single-stage compressor (right of stage) is one that we have studied during our research. These are its rotor blades. This is a stationary row of blades which is usually installed ahead of the rotor blades in this fashion. The stationary blades mounted at the compressor inlet are called inlet guide vanes. Both the stationary blades and rotor blades are so mounted that they can be easily replaced for research on successive sets of blades of varying design. The performance of this compressor with a conventional set of blades is shown in the next chart (C-35921). Stage efficiency is plotted against Mach number relative to the rotor blades. You can see that, as the Mach number is increased above values of approximately 0.7, the efficiency rapidly decreases. The phenomenon in this compressor stage is, therefore, very similar to that indicated in the movie of the isolated airfoil.

This efficiency characteristic explains why inlet guide vanes are being used in our present-day compressors. The inlet guide vanes are so designed that they keep the Mach number of the air relative to the rotor down to the low values of approximately 0.7 so as to maintain good efficiency. Sacrifices in efficiency of the magnitude indicated in this chart above 0.7 Mach number cannot be tolerated. It is desirable that the stage efficiency be maintained constant out to the high Mach numbers as indicated by this curve. Our research has indicated that efficient operation at these higher speeds requires use of blade shapes which are somewhat different from the conventional shapes and new design techniques. Good progress is being made toward obtaining characteristics such as this. We can then use the higher air speeds and blade speeds I have discussed and remove the inlet guide vanes from the compressor. (Drop C-35921)

Let us now physically demonstrate the resulting gains in performance obtained by increasing the speed of a compressor and by removing the inlet-guide vanes. Let us observe the performance of this compressor in order to determine experimentally the effects of of blade speed. I'll now start the compressor. On these three dials (upper right) are indicated the rotor speed, the air flow, and the pressure rise. As I increase the rotor speed, you can see that the air flow and pressure rise also increase. You can see that both the pressure rise and the air flow have been increased by raising blade speed. (Off) I'll now remove the inlet guide vanes to see how effective this method of achieving high performance actually is. (Remove guide vanes.) Now let's see what flow and pressure rise we get from this stage when we run it at the same blade speed as we previously did. (Turn compressor on.) You can see that the air flow and pressure rise are both considerably increased. (Off)

We have shown, therefore, that increases in compressor flow, and therefore in engine thrust, are possible if the air velocities into the stage and the blade length could be increased for a given outside compressor diameter. In addition, the compressor length could be reduced by reducing the number of blade rows required if we could increase the blade speeds and the air speeds.

These improved performance characteristics would permit us to build engines similar to this model engine (upper left). This engine represents our research goal. It consists of a three-stage compressor operating without any inlet guide vanes at blade speeds appreciably higher than those in current use. The higher blade speeds would permit use of a single-stage turbine which is no bigger in outside diameter than the compressor. Such an engine would be both simpler and lighter for any required thrust than our current engines.

Of course, there are mechanical problems in addition to the aerodynamic ones associated with the high air and blade speeds of this model engine. These higher speeds and the longer blades that I mentioned earlier lead to large forces on the compressor blades and on all the rotating parts of the engine. Some of these mechanical problems will be discussed by the next speaker.

Part II - Rotating Stall and Blade Vibration Problems

by Francis C. Schwenk and James J. Kramer

In the operation of turbojet engines of the type exhibited here, we have observed violent blade vibrations and violent air flow fluctuations which may prevent the complete use of the aerodynamic advances discussed previously. As a matter of fact, these vibrations and flow fluctuations have caused serious mechanical failures in some engines. Observe this slide (CS-8851), for example. This is a compressor casing of an engine which experienced such a failure. Note that the casing was sliced into two parts by a failed rotating blade row. This slide (CS-8850) shows the rotating member of the same compressor. Note that all rotor blades are damaged and that one complete blade row is gone.

It is obvious from these pictures that hazardous failures can occur. Furthermore, the possibility of failure can be expected to increase in the compressors for these proposed light weight, high thrust engines because of the higher operating speeds and longer blades.

Consequently, the causes of engine failure are being investigated by the NACA, and I would like to tell you something of what we have learned.

One important cause of complete failure is blade vibration. As late as 1 year ago the cause of blade vibrations was not clearly understood and destructive vibration would frequently occur under very embarrassing circumstances. However, we have recently discovered the important exciting force which causes the vibrations and I shall now describe this force.

Among operating conditions for which we have observed compressor blade vibrations are the low-speed and off-design points. A study of the flow at these poor conditions revealed a completely new phenomenon called rotating stall. There is strong evidence to show that these rotating stalls excite the blade vibrations.

Let us examine this phenomenon of rotating stall and determine how it excites blade vibrations. First we must point out what we mean by the term "stall." In this slide (CS-8854), the airfoil on the left is operating at its design condition and the air passes smoothly over its surfaces. However, the airfoil on the right is operating at a poor flow condition similar to that in a compressor at off-design operation. Note that the air flow breaks away or separates from the surface and the airfoil is said to be stalled.

We will now consider the manner in which a series or cascade of airfoils will stall. At first thought one might expect that the blades will stall simultaneously as shown on this slide (CS-8852). However, this does not occur. Due to unavoidable nonuniformities in the blades and flow direction, only one blade or a few adjacent blades will stall, and form a stall zone, as shown in this slide (CS-8855). The stall zone will propagate along the cascade or, in the compressor case, will rotate around the blade row (CS-8857). As many as 12 separate stall zones have been observed in some of our compressor stages. (Remove slide.) The rotation of the stall zones relative to a compressor blade row can be pictured by my placing this plastic disk next to the compressor model (on backdrop at right center). The colored portions represent the stall zones which include several adjacent blades. The stalled region moves from one group of blades to the next like this.

The rotating stall zones cause the aerodynamic forces on the blade to vary periodically with time. If the frequency of the forces equals the natural frequency of the blade, serious vibrations can result. We can demonstrate this effect by this model of a compressor blade row (backdrop, left center). The steel strips represent compressor blades, the two regions on the disk represent rotating stall zones, and magnetic forces simulate the aerodynamic forces. (Start) The rotation of the disk will cause a periodic force on the blades. The speed of the disk will increase until the frequency of the magnetic forces will equal the natural frequency of the blades. At that condition a noticeable vibration should appear. Observe that the blades are now vibrating. The light from the stroboscope slows down the action and enables us to see that the stall zone and the blade move in unison. This fact indicates that the blades and the stall have the same frequency. It is in this manner that rotating stalls cause vibrations. Experience has shown that the resulting vibrations are of a sufficient magnitude to cause blade failure. Now that we understand the mechanism causing these vibrations we are in a much better position to do something about them, and some possible solutions have already become apparent.

Another type of violent flow fluctuation called "surge" is associated with compressors. These fluctuations appear under certain conditions of engine acceleration and are again related to rotating stalls. The violence of the surge will be demonstrated in the following movie.

The first scene (control room of PSL with J73 on test) shows the variation of several engine performance variables on a recorder during acceleration of the engine. First, we will observe the engine characteristics during a slow acceleration caused by a small increase in the fuel flow rate. (Movie on.) Notice that the engine performance variables change smoothly after the small increase in fuel flow rate. (Movie off.) Sometimes it is necessary to accelerate the engine rapidly, for instance, to expedite take-off of an interceptor aircraft. Now we will observe what happens during very rapid acceleration caused by a large increase in fuel-flow rate. (Movie on.) Notice that after the large increase in fuel-flow rate the other engine performance variables oscillate rapidly. (Movie off.) These rapid oscillations are an indication of engine surge.

The next scene (P&W J57 in Altitude Wind Tunnel with sound track of surge) will show the tail pipe of an engine operating in surge conditions as shown in the last recorder scene. The rapid oscillations on the recorder will be manifested in a violent vibration of the engine and a combustion instability. (Movie on with sound.) (Movie off.)

Since surge is triggered by rotating stalls, a solution of the blade vibration problem through elimination of rotating stalls will also tend to cure the surge difficulties.

We have shown that the phenomenon of rotating stall is the source of serious mechanical difficulties -- blade vibrations and engine surge. We have made some progress in avoiding rotating stalls and surge but further work is necessary to realize the full potential of the aerodynamic advances discussed previously. Consequently, the NACA is testing turbojet engine components of advanced design in order to gain the fundamental aerodynamic and mechanical information necessary for the design of these proposed light-weight, high-thrust engines.

As a summarizing demonstration for this discussion, we will run a research turbojet engine having a compressor of advanced aerodynamic design and observe its performance and operational problems. By the running of this engine we will demonstrate some of the research techniques used to study the vibrational problems. Mr. ________ will take over this phase of the demonstration.

Part III - Demonstration of Rotating Stall and Blade Vibration in an Advanced Compressor

by Robert R. Ziemer and William H. Robbins

The engine we will run is a current model with the compressor replaced by one that we have designed. The compressor design includes the ideas, discussed by Mr. _______, of increasing the engine thrust through a greater air-flow capacity; also the number of compressor stages has been reduced by the use of higher stage pressure ratios. In other words, this engine is a step in the direction of producing the high-thrust, light-weight engine shown here. The purpose of testing such an engine was to explore the aerodynamic potentialities and to study the rotating stalls and blade vibrations in a compressor of advanced design. Today we wish to show you how the engine runs and also indicate the methods used to observe the rotating stalls and blade vibrations in such an engine.

During the operation, the engine speed will be indicated on this dial (overhead center) and rotating stalls and blade vibrations will be represented on these oscilloscopes (overhead center). Before we start the engine, I would like to show you what to look for on the oscilloscopes. When the oscilloscope trace appears as it does now, the air flow is smooth and no vibrations are present. The trace on the right is the result of a parasitic feedback. When the traces appear as they do in this slide (CS-8906), rotating stalls and blade vibrations are present. In order that the operator can hear my instructions, my microphone is connected to a speaker in the control room.

Speaker: Are you ready to start the engine?
Operator: We are all set to go.
Speaker: Start the engine and set the speed at 30 percent of design speed.

The engine is now being accelerated to idle speed. The trace on the oscilloscope at the left shows the signal generated by an instrument fixed in the compressor casing. This instrument senses the fluctuations in flow velocity, and, therefore, the rotating stalls. You can observe that at this operating point there are rotating stalls, evidenced by the peaks and valleys of the oscilloscope trace.

The trace on the oscilloscope at the right shows the blade vibrations caused by rotating stalls.

As the blades in this compressor vibrate, so does this trace oscillate. Furthermore, the greater the amplitude of the trace, the more serious are the vibrations. The vibrations now are not serious, however.

Speaker: Accelerate the engine, please.

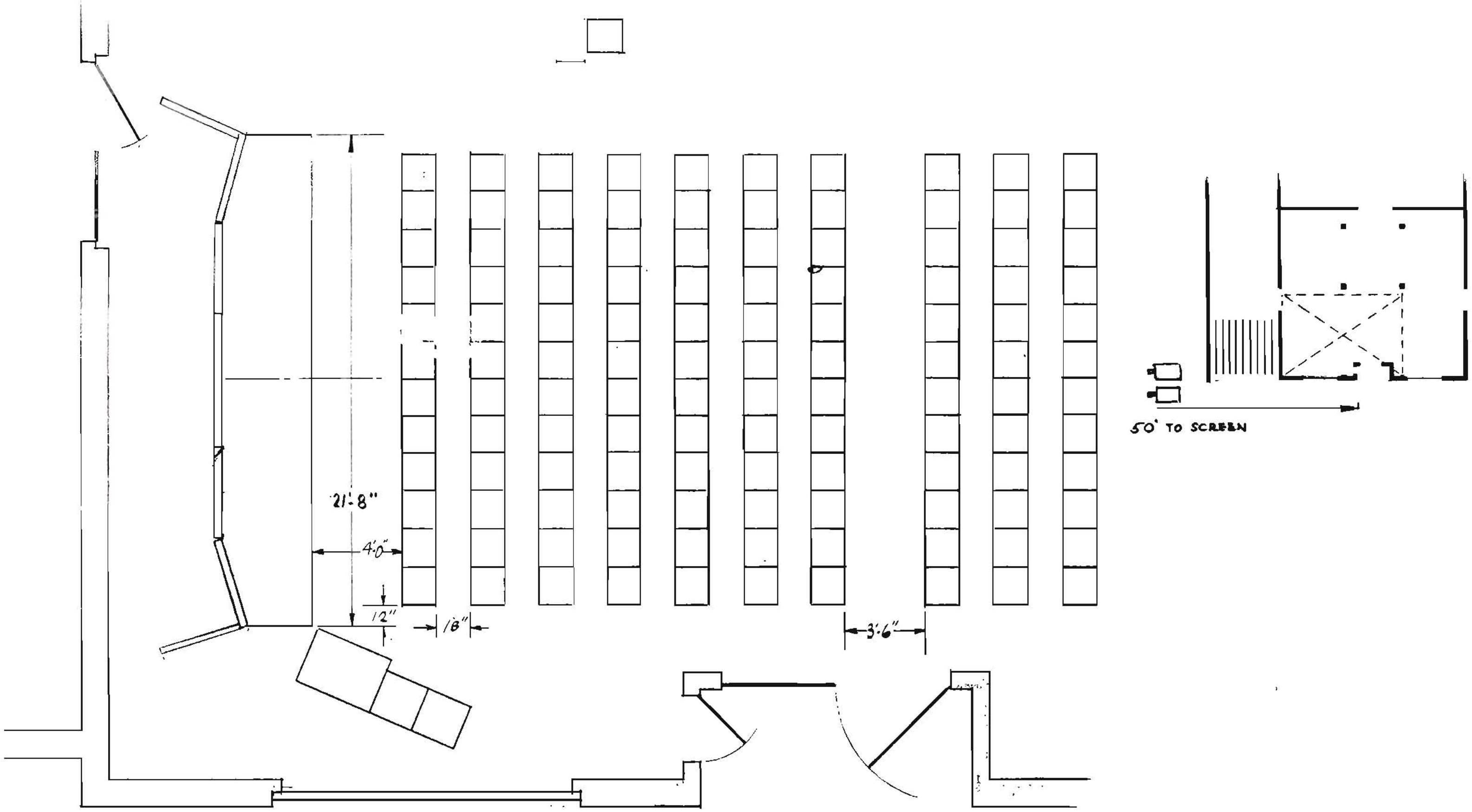
The sudden increases in amplitude of the vibration trace indicates a resonant condition between the rotating stalls and the natural frequency of the blades. These resonant conditions present the most serious vibration stresses. The engine is not operated at these conditions for a long period but is accelerated through them as we are now doing.

I would like you to pay special attention to the sound level of the engine. Because, as the engine speed increases, the compressor will eventually reach a better operating condition for which there are no rotating stalls. You should be able to hear a definite change in the sound and to see on the oscilloscope that the rotating stalls disappear. And, of course, the blade vibration stresses will lessen considerably. There, we are now at stall-free operation, and no rotating stalls or blade vibrations are shown on the oscilloscopes.

(To operator: Shut down the engine, please.)

The thrust characteristics of this engine at design speed are appreciably better than current models. This increase in thrust was made possible by incorporating compressor aerodynamic advances discussed in the first part of the demonstration. These advances, you will remember, are high air-flow capacity and high-stage pressure ratio without sacrifices in efficiency.

In the second part of the demonstration we have indicated that destructive blade vibrations and engine surge are caused by rotating stalls which are also prevalent in these advanced designs. By the operation of the engine of advanced design we have shown the research equipment used to provide the aerodynamic and mechanical information necessary for producing high performance engines in order that U. S. air supremacy can be maintained.



1954 INSPECTION

ENGINE PROP. RESEARCH BUILDING
LEWIS FLIGHT PROPULSION LAB.
SCALE 1/4" = 1'-0"
COMPRESSOR & TURBINE RES. DIV.

WHA 5/18/54
JJm 5/18

REV. C - 5-21. R.S. PROJ. DIST.

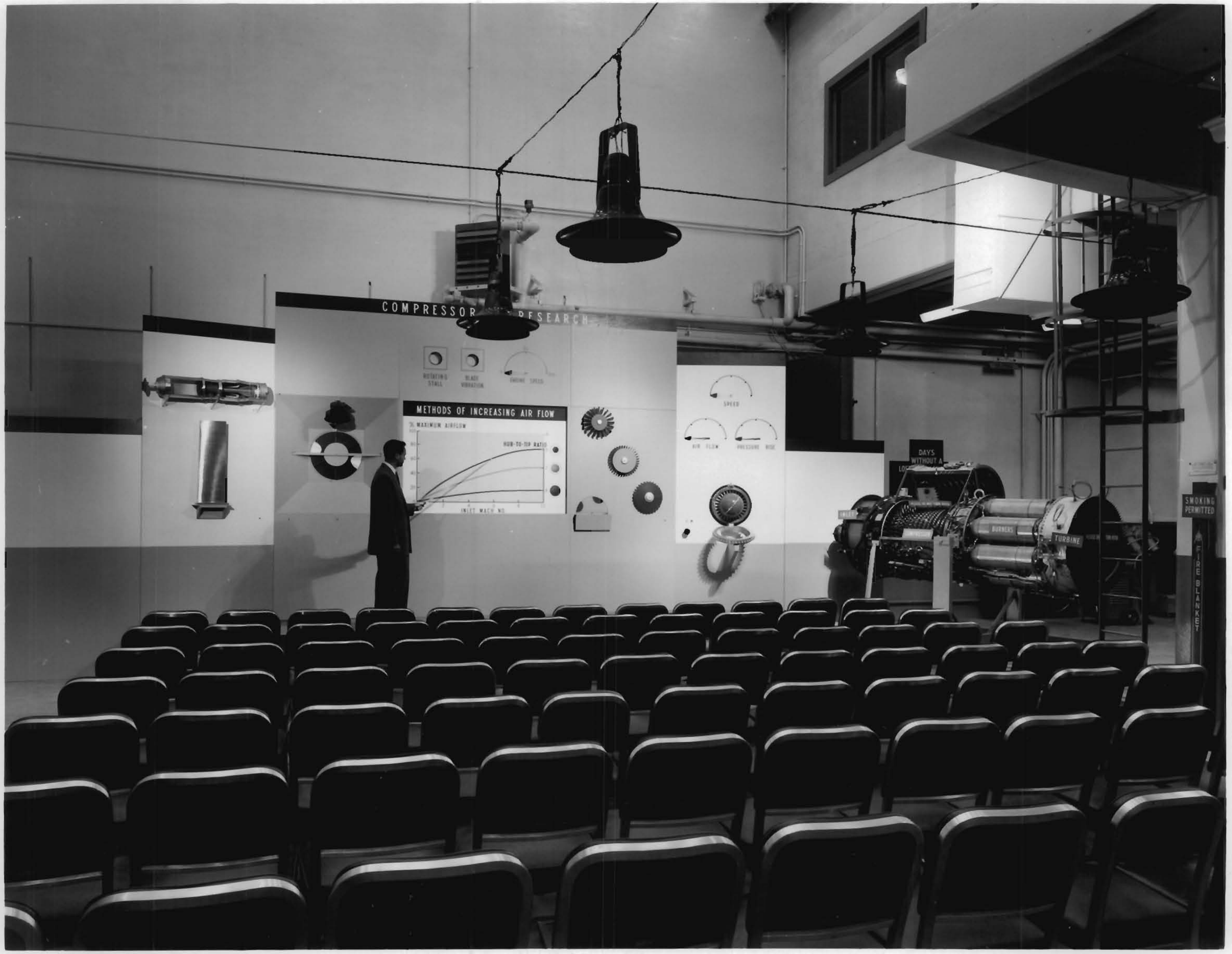
REV "A" - 5-3-54

SEAT WIDTH - 20"

REV B - 5/19/54

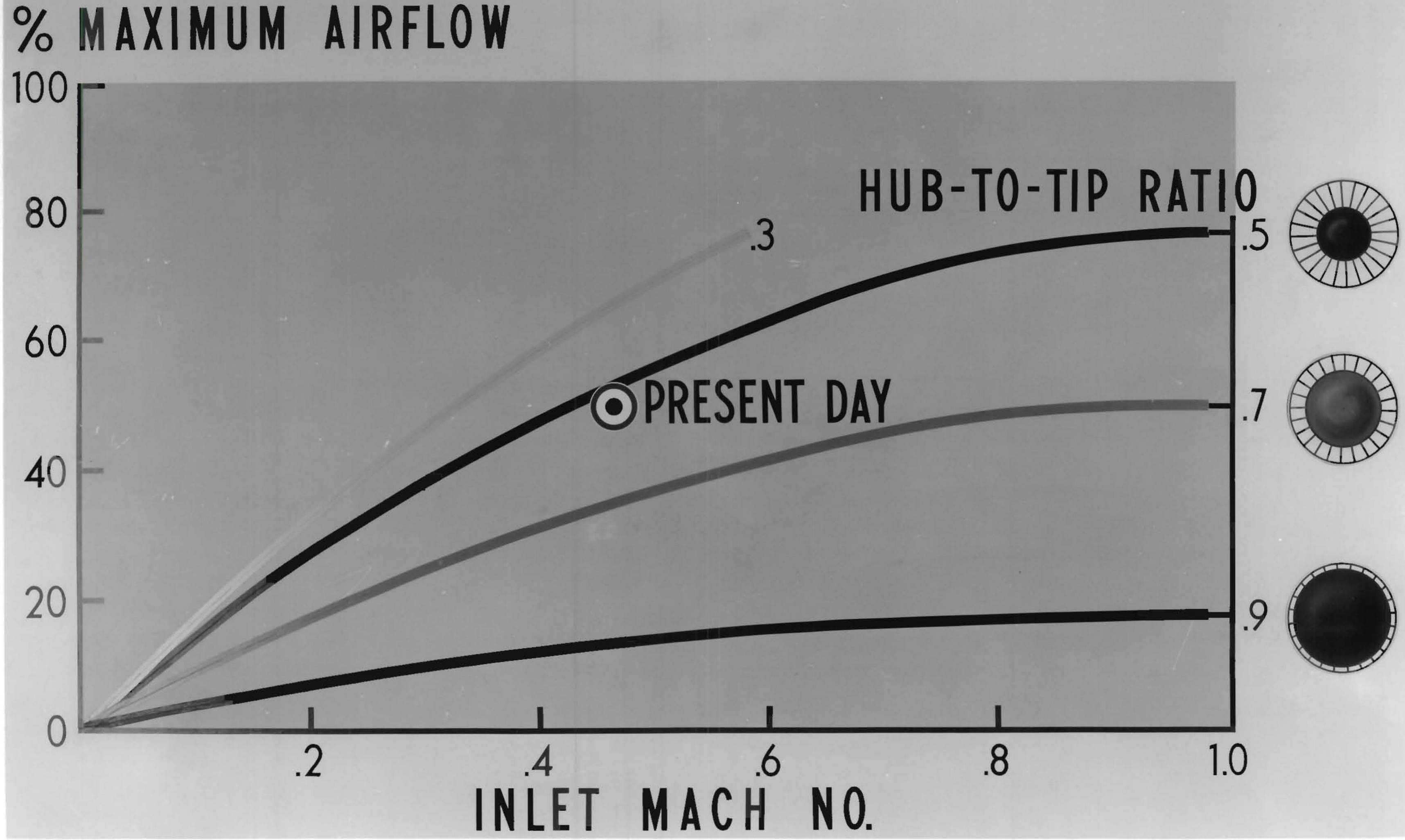
NACA

C-36014


COMPRESSOR RESEARCH
ROTATING STALL
BLADE VIBRATION
ENGINE SPEED
METHODS OF INCREASING AIR FLOW
% MAXIMUM AIRFLOW
HUB-TO-TIP RATIO
INLET MACH NO.
SPEED
AIR FLOW
PRESSURE RISE
DAYS WITHOUT A
INLET
BURNERS
TURBINE
SMOKING PERMITTED
FIRE BLANKET

NACA
C-35915

METHODS OF INCREASING AIR FLOW



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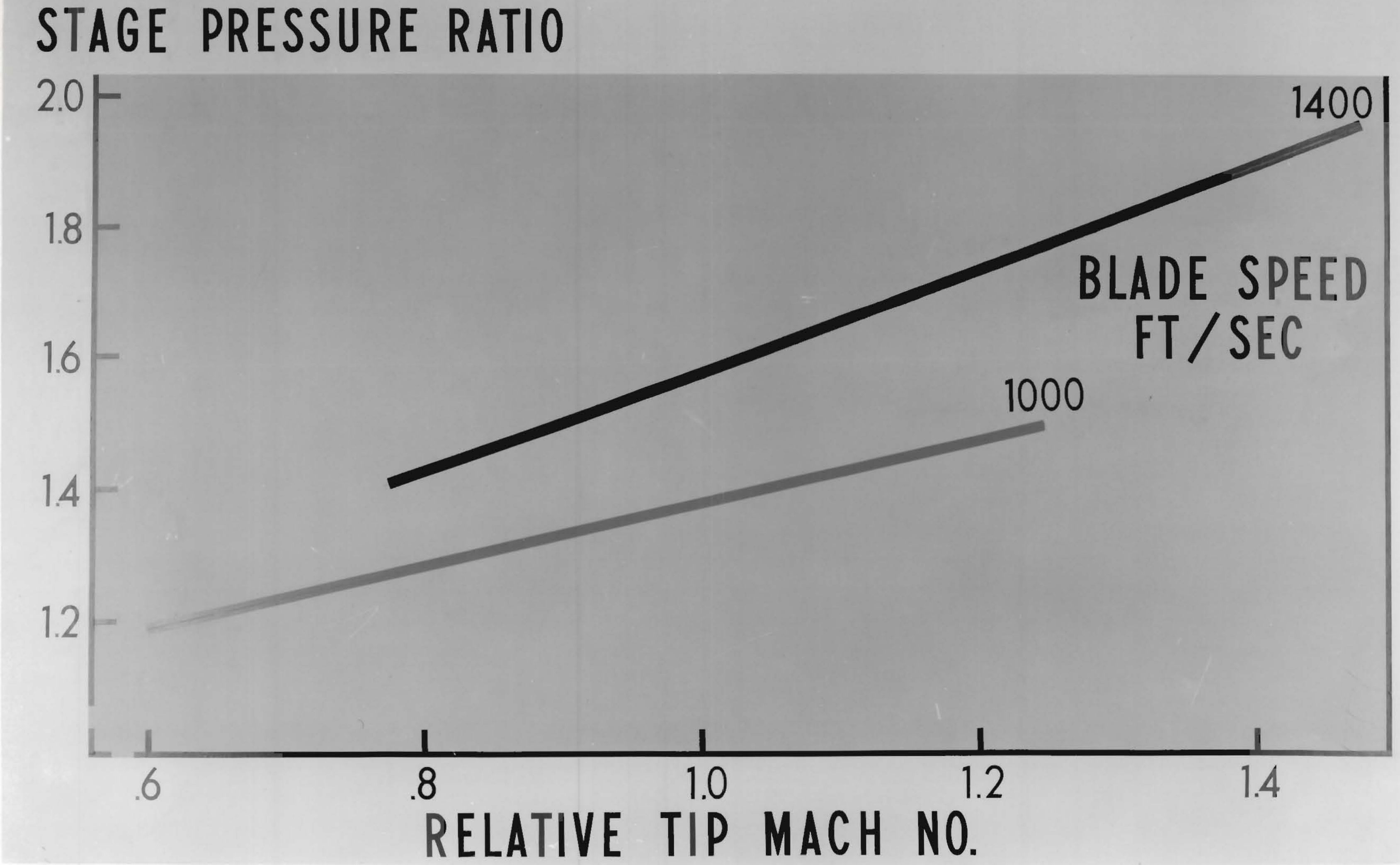
METHODS OF INCREASING PRESSURE RATIO



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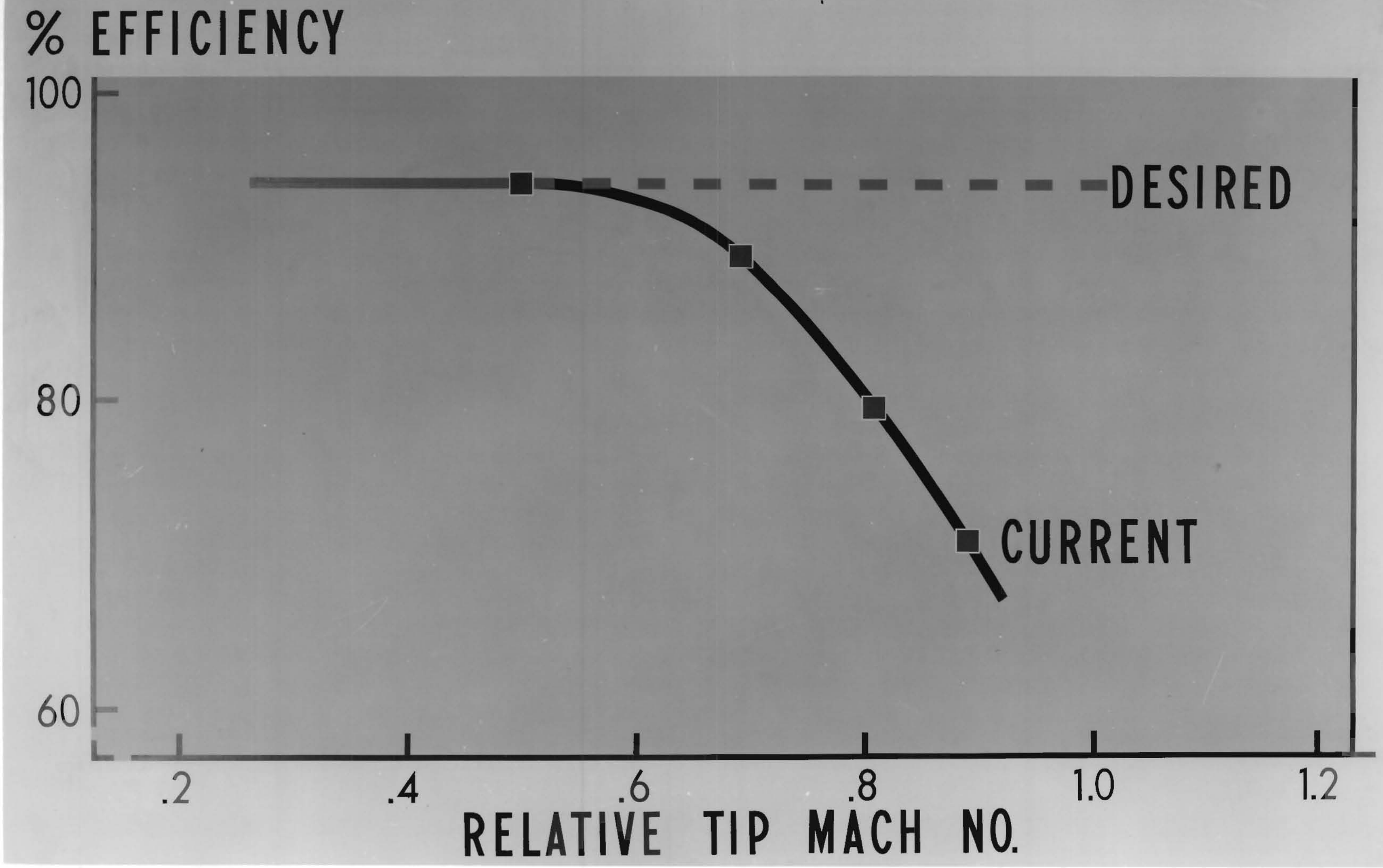
EFFECT OF MACH NO. ON EFFICIENCY



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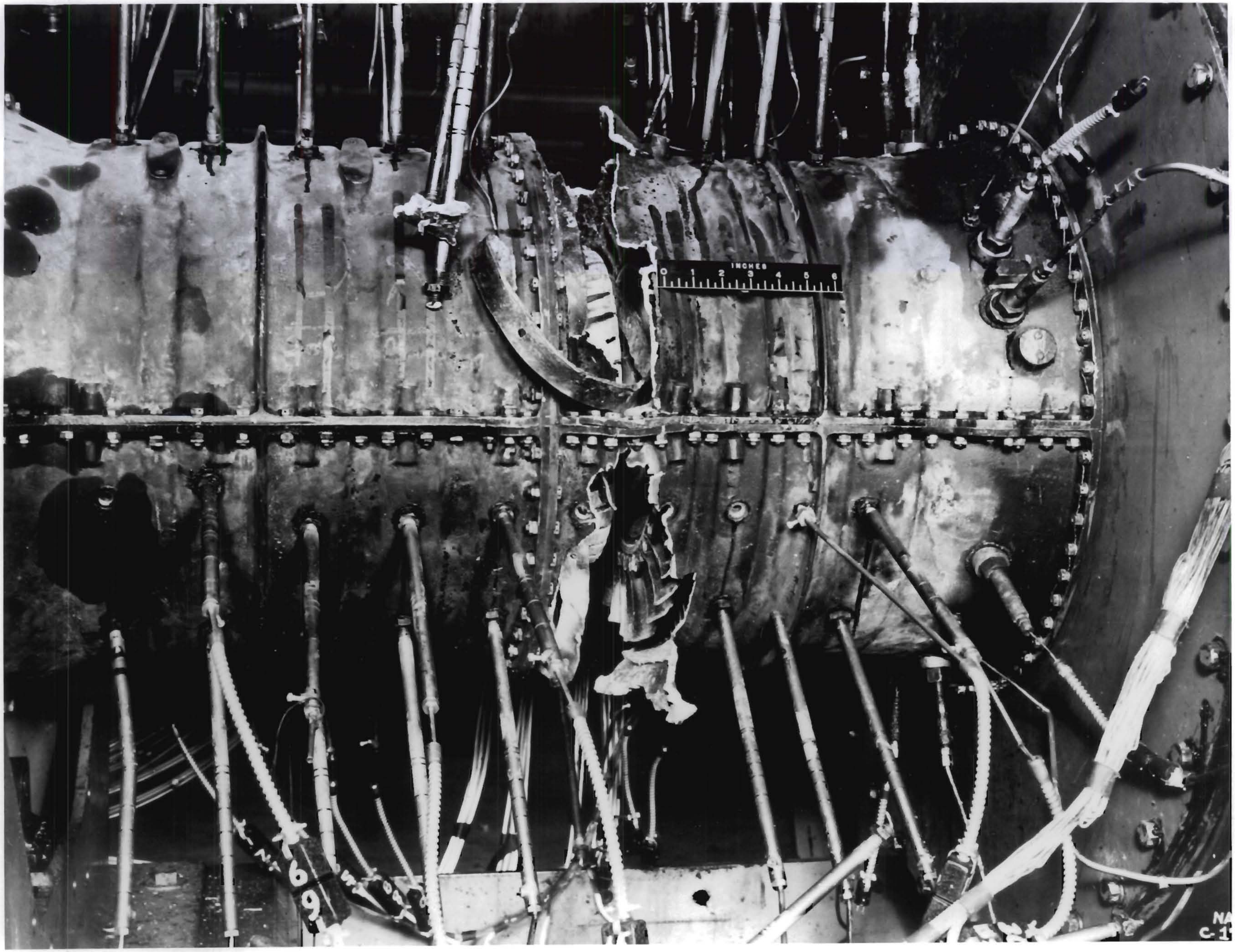
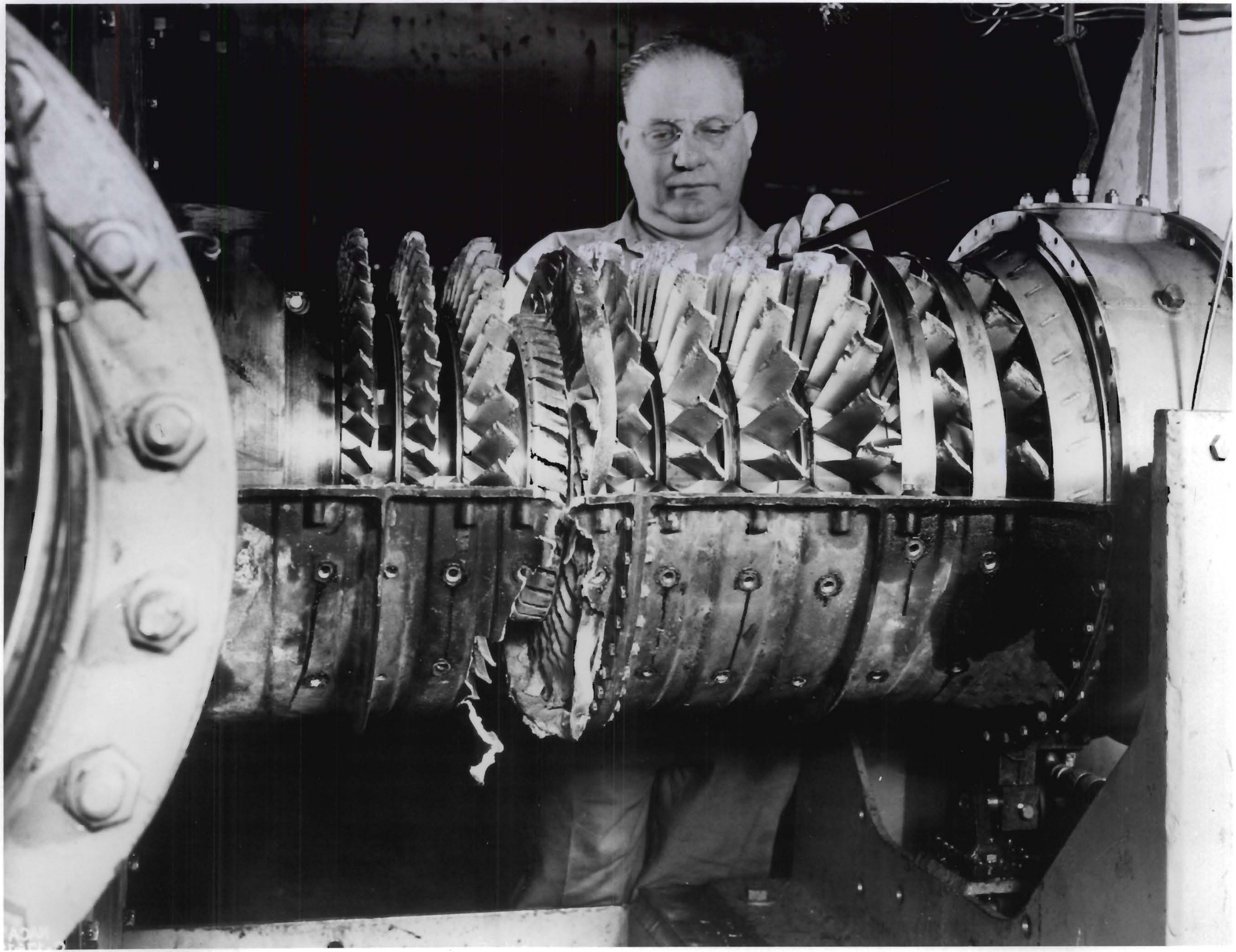
CS-8851

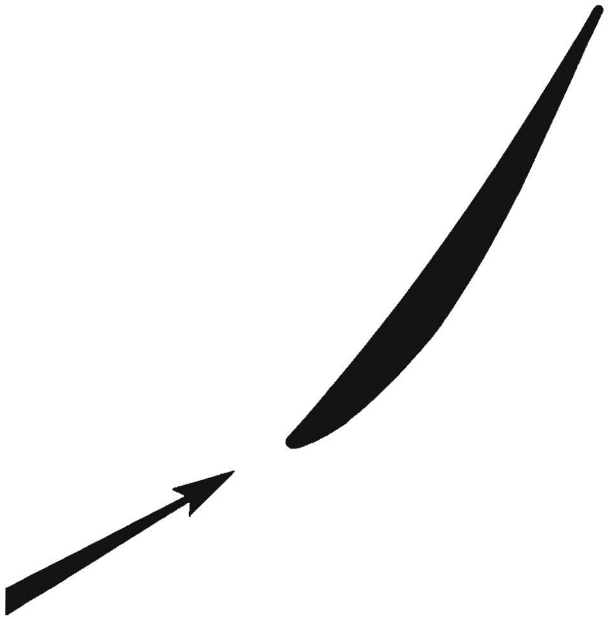


CS-8850



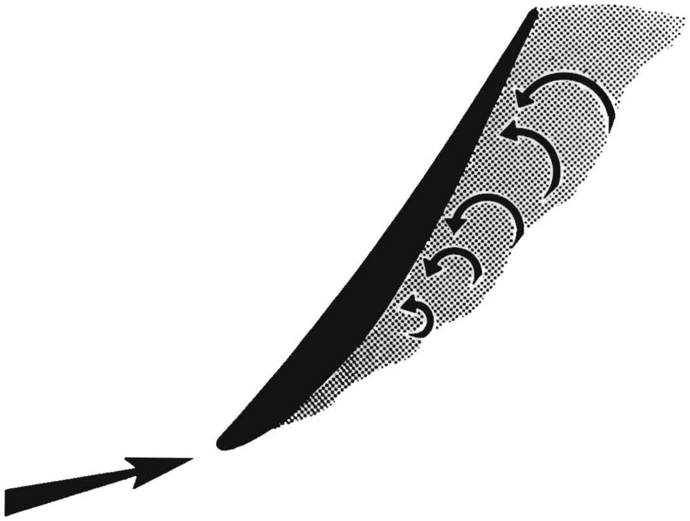
SINGLE AIRFOIL

DESIGN
FLOW

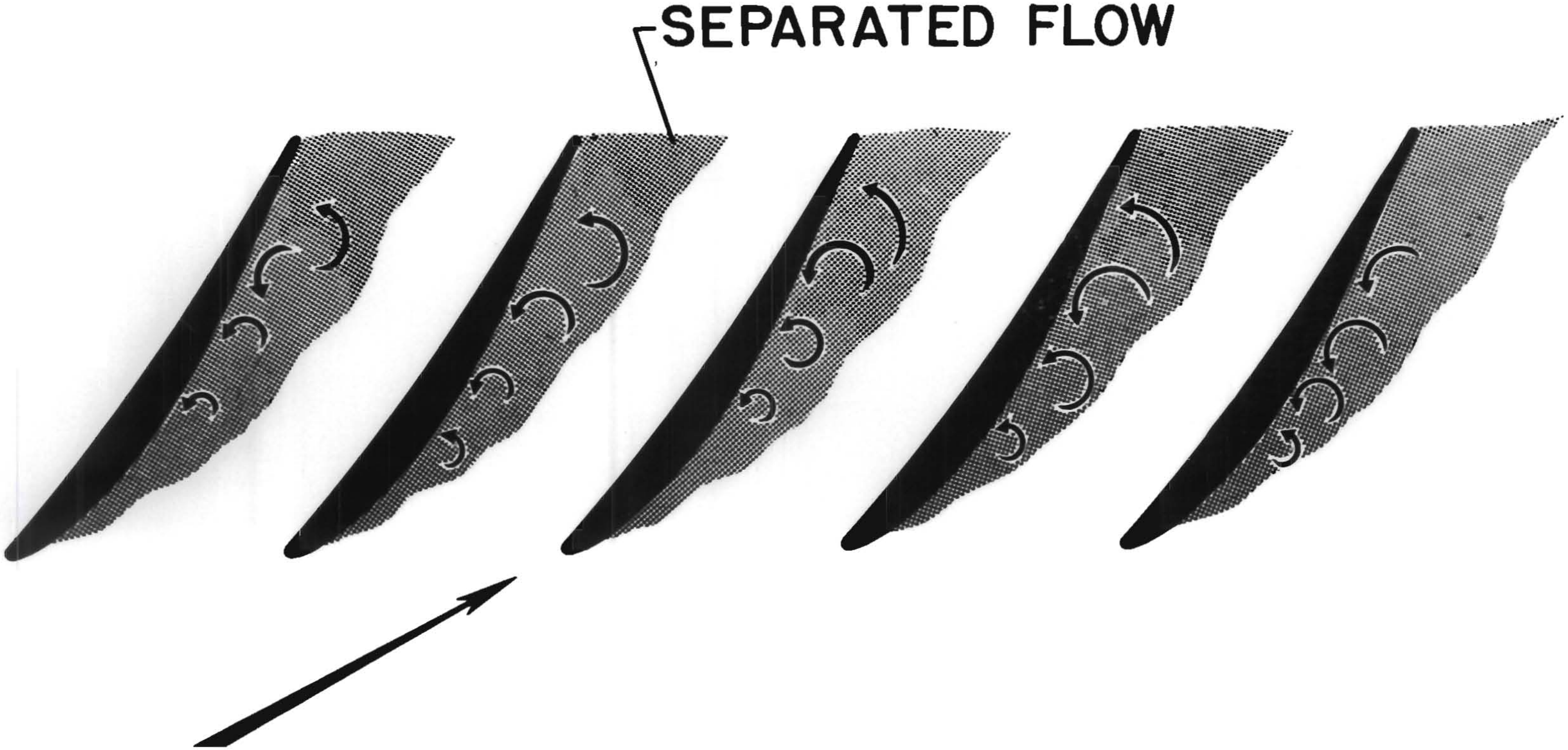


SINGLE AIRFOIL

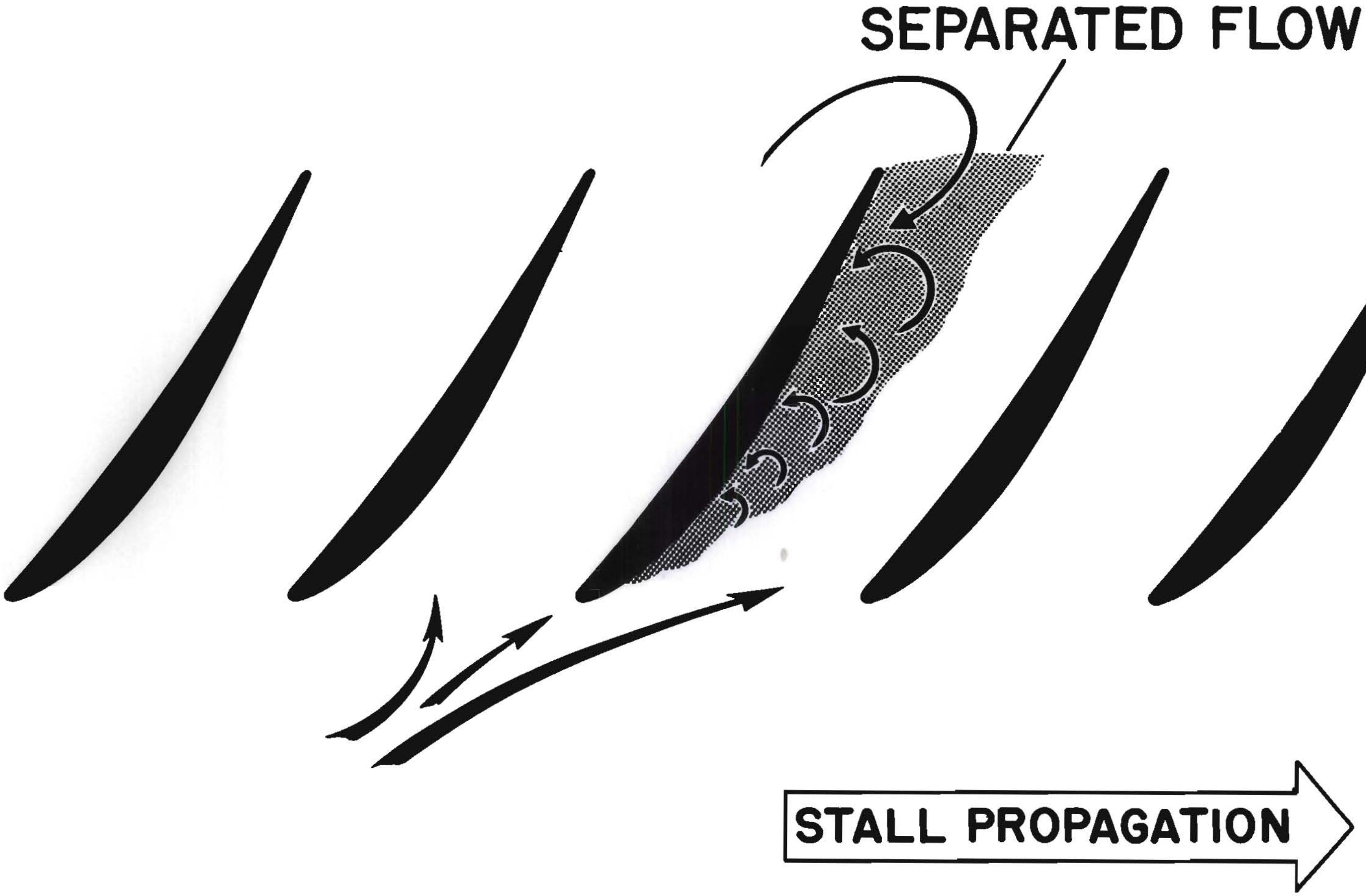
OFF-DESIGN
FLOW



UNIFORM STALL



PROPAGATING STALL



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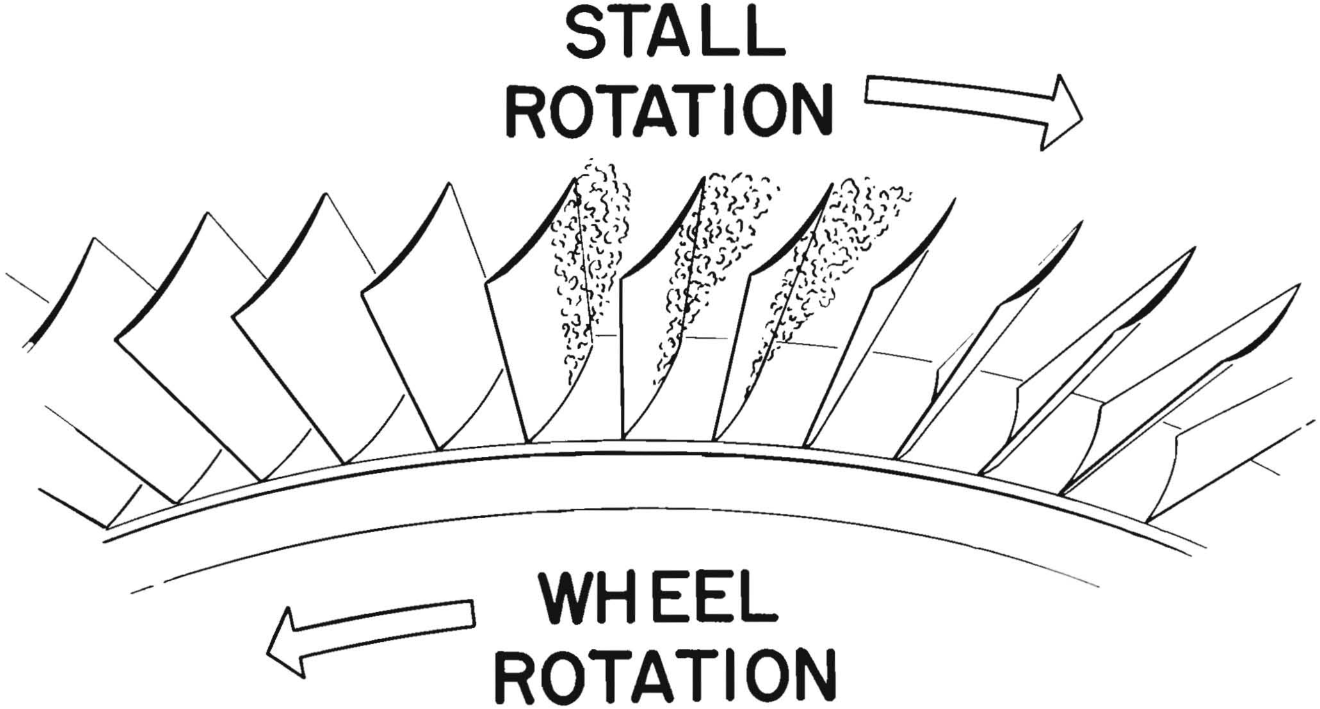
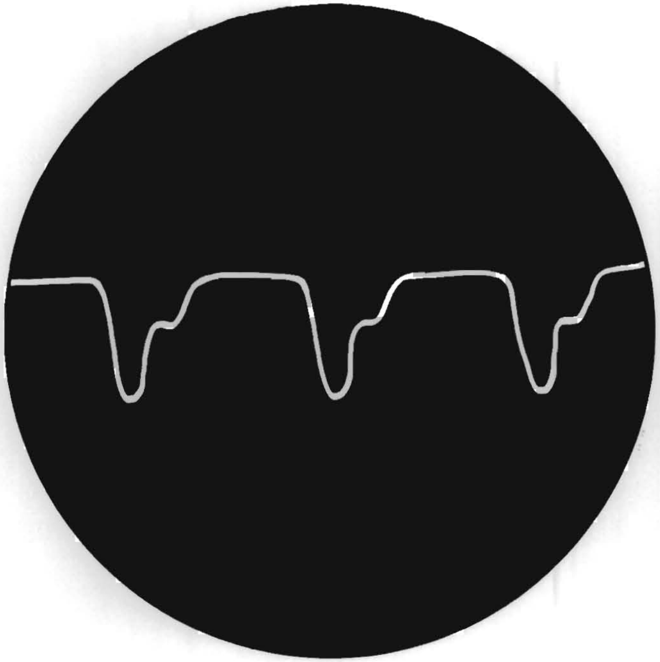
CS-8857

ROTATING STALL

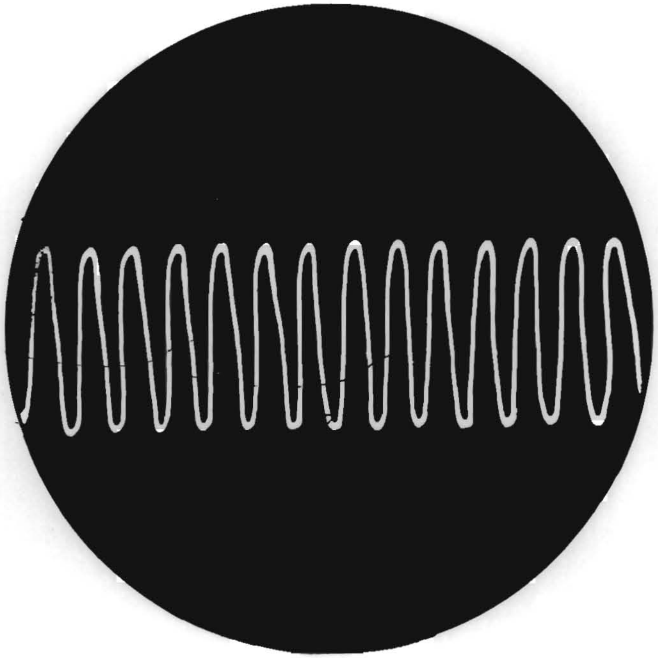


CS-8906

OSCILLOSCOPE TRACES



ROTATING
STALLS



BLADE
VIBRATIONS