1949 INSPECTION OF THE NACA LEWIS LABORATORY

TALKS ON TURBINE COOLING

Cascade and Single-Stage Research

Speaker - Richard J. Rossbach

One of our most important fundamental problems, as just pointed out by Mr. Arne, is to develop a method of predicting the amount of heat flowing from the hot gases to all points on cooled turbine blades. A knowledge of the heat flow is required so that a cooled turbine blade can be designed to use a minimum coolant weight flow and still have adequate cooling to prevent blade failure due to overheating. For instance, it is possible that this (point to models of blade cross-sections on backdrop) portion of the blade might be hotter than this portion (point) due to a larger amount of heat flowing from the hot gases around the blade to this portion (point) than to this (point). Thus, the coolant flow in this region (point) must be increased, but it is advantageous to reduce the coolant flow in this region (point) so as to effect a saving in the attendant losses. Heat transfer can be predicted with reasonable accuracy for heat flow from gases to simple bodies, such as pipes and cylinders. The generalization of heat-transfer results for flow through pipes is discussed at another location on your itinerary. In the case of turbine blades, the heat-transfer problem is quite complex because of the variable aerodynamic conditions, blade shapes, and high rotational speeds. Consequently, experimental data must be obtained on turbine blades in order to accurately predict the heat transfer. In order to obtain these fundamental data, we are using at present seven cascades and three single-stage turbines.

Typical heat-transfer results obtained from the simpler cascades are illustrated on chart 1 (C-24185-B). The amount of heat transferred to the blade is plotted against the amount of hot gases flowing over the blade. The results on this and following charts are obtained by passing a mean line through the data points. The results are for one blade shape and one angle of attack. The blue line represents the results for this (point) blade arrangement and the yellow line represents the results for this (point) arrangement. These results are represented by two distinct curves. This is due to the shape of the passage between the blades. As you can see, this one (point) necks down and this one (point) does not. Experimental results have also shown that the amount of heat transferred varies with the blade shape itself and the angle of attack. These factors which affect the heat flow may cause as much as 50-percent variation in the results. We can conclude, therefore, that if such tests continue to be required as a method of obtaining heat-transfer results for turbine blades, it would be necessary to provide the designer with experimental heat-transfer data for each new turbine design. This would be a very long-term and expensive project. As a consequence, we are investigating the fundamentals which control the heat transfer so that we can predict the heat transfer at any point.

The NACA is attacking this basic problem of heat transfer through a study of the very thin layer of gas, called the boundary layer, which has been retarded by friction along the blade surface. Chart 2 (C-24185-A) is a sketch of the flow around a turbine blade, with the heavy line adjacent to the surface representing the extent of the boundary layer. All the heat transferred to the blade must pass through this boundary layer, which will therefore control the amount of heat transferred. Two types of flow may develop in the boundary layer. The flow moving in parallel sheets as shown on the front part of the blade (point) is called a laminar boundary layer and the circular, rolling flow shown at the rear of the blade (point) is called a turbulent boundary layer. A blade may have either a laminar boundary layer alone or a combination of both types. The amount of heat transfer through a laminar boundary layer differs from that of a turbulent boundary layer. We must know the temperatures and pressures in the boundary layer in order to compute the amount of heat transfer. The NACA is now expanding the abstract theory with which the temperatures and pressures in the laminar boundary layer with heat transfer can be computed. Experimental apparatus are available for verifying the results calculated from boundary-layer theory. This (point) cascade is one piece of apparatus being used for this purpose. The very large number of measurements that can be obtained is apparent from this maze of approximately 100 wires constituting the instrumentation which provides the required pressure and temperature data on the blade.

A comparison of some heat-transfer results obtained using the theory of the laminar boundary layer with those from a cascade is shown in chart 3 (C-24186-A) to indicate some of the progress that has been made in the past year. The amount of heat transferred to the blade is plotted against the amount of the hot gases flowing over the blade. The red curve represents the results predicted from the theory for the laminar boundary layer as expanded to date by the NACA to include heat transfer. The blue curve represents the results of experiments conducted with a cascade of cooled turbine blades which were of such a shape that the boundary layer was probably all laminar around the blade. In this particular case, the maximum variation between the predicted and experimental results is 7 percent. This is considered good agreement. With refinements in the theory, further comparisons which are to be made are expected to be better than these results. Such verification of theory will expedite the obtaining of knowledge concerning cooled blade design and appreciably reduce the amount of expensive development required.

Complete similarity of the flow in cascades and rotating turbines cannot be realized. Therefore, because it is advantageous and sometimes necessary to conduct heat-transfer studies in cascades, means must be devised for applying these results to the design of cooled turbines. This is accomplished through the analysis of cascade and single-stage results like those shown on the next chart (C-24186-B). Again the amount of heat transferred to the blade is plotted against the amount of hot gases flowing over the blade. The blue curve represents the results for the cascade of blades. The red curve represents the results obtained from a single-stage turbine like this (point) under actual operating conditions and with approximately the same shape blades as in the cascade. The comparison is considered excellent when it is realized that certain conditions in turbines cannot be duplicated in cascades. The maximum variation between these results is 7 percent. If further comparisons are as good or better than these results, we probably will be able to expedite the development of a method for applying cascade results directly to the design of cooled turbines.

In closing, I will briefly summarize this and the preceding talks on compressors and turbines. We have presented the scope of our research and some of the important results that have been obtained in the past year. We have made significant advances in our theoretical work, both in compressor and turbine aerodynamics and in turbine cooling. By augmenting our theoretical work with cascade, single-stage, and multistage research, we have been able to improve compressor and turbine performance. By means of the research program outlined, we will be able to accomplish our objectives, as originally set forth by Mr. English- that is, engines with higher power, and lower specific fuel consumption, and in addition make use of inexpensive nonstrategic materials.

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TALKS ON TURBINE COOLING
Theoretical Research
Speaker - Vernon L. Arne

(See Stage Photo C-24157 and Color Photo)

Gentlemen, this exhibit will show some of our work on turbine cooling. The purpose of turbine cooling is to increase power, economy, and reliability of gas-turbine engines and to conserve scarce, or strategic materials.

The power, and in some cases, the economy of gas-turbine engines can be improved when the gas temperatures and pressures at the turbine inlet (point to engine) are increased. For instance, calculations have shown that the power can be more than doubled when the temperatures are increased from 1500° to 3000° F. At present, however, the gas temperatures at the inlet are limited to about 1500° F because of stress limitations of the blade materials at high temperatures, even though the best high-temperature materials presently available are used. These heat-resisting materials also have a large quantity of alloying elements in them which are scarce; for instance S-816, a material widely used for turbine blades, has 96 percent of such alloying elements. Because of this alloy shortage, there is grave doubt that the quantity of engines required for a war-time air force could be supplied. Heat-resisting materials are more fully discussed in the materials presentation.

One possible method of solving the problem of obtaining present-day performance or better with materials which have as low as 2 percent of strategic alloys is to cool parts of the engine. This applies especially to the turbine blades which are in direct contact (point to engine) with the hot gases coming from the combustion chambers. The blades are highly stressed because of the high rotative speeds of the turbine. By cooling, the materials will operate at lower temperatures where even the common steels have high strength.

Analytical results have shown the relative effectiveness of various ways of cooling blades. Water is the more effective coolant but has the disadvantage of requiring a radiator and closed coolant system. The analysis of air-cooled blades showed the internally finned, hollow blade (point to model) to have a higher effectiveness than the plain, hollow blade. During the past year, the NACA has found methods of fabricating finned blades for research purposes. Finned blades have been cast and others have been made by pressure-welding the component parts. Here (hold up model) is a finned blade made by pressure-welding and it is similar to the enlarged cross-section view shown here. Another method of cooling being considered is the use of porous blade materials through which coolants can be forced.

The following demonstration will compare the effectiveness of various blades. The solid, uncooled blade; the plain, hollow, air-cooled blade; the finned, air-cooled blade; and the water-cooled blade will be compared. Here is a duplicate set of blades which is the same as the one mounted in the duct. (Hold set in duct). Enlarged cross-section views of the blades in their respective positions are shown here beside the indicators which will show the temperatures of each of the blades. Hot gas at about 1000° F will be produced in a burner and will pass over the blades. The temperature of the hot gas will be shown here.

When the hot gas flows into the rig, the blade temperatures will all be close to the temperature of the hot gas since no coolant will be used. When cooling air is drawn out of the room through the plain, hollow blade, you will notice a reduction in the blade temperature (point) of about 100° below the temperature of the uncooled blade. When the same amount of cooling air is passed through the finned blade, the drop in temperature will be about twice that of the plain, hollow blade. This will verify the calculated beneficial effect of internal fins. When the same weight flow of water is passed through the water-cooled blade, a rapid drop in blade temperature will be noticed. The temperature drop will be about four times that of the plain, hollow blade. This definitely indicates the effectiveness of water as a coolant.

The results of tests of cascades similar to the one just demonstrated show the relative effectiveness of various cooled blades. The problem of predicting cooled engine performance involves much more than a simple evaluation of the cooling effectiveness of the blades. The cooling losses, such as the heat lost to the coolant and the power required to circulate the coolant must be considered. At last year's inspection, we presented the results of analyses estimating the amount by which gas-turbine temperatures could be increased using different types of cooling. We also showed the potential or ideal gains in engine performance offered by higher turbine gas temperatures, but we were unable to predict accurately the net performance of an engine including the cooling losses. In the past year we have developed methods that enable us to predict the approximate performance, including losses.

Chart 1 (C-24181-C) shows the possible gains in power of a cooled turbine-propeller engine operating at best pressures at 40,000-foot altitude. Theoretical increase in power is plotted against the weight flow of the coolant expressed a ratio of coolant flow to the weight flow of engine air. Present-day operation at 1500° F turbine inlet temperature is represented by the circle at the lower left-hand corner of the chart. The gain in power of the uncooled engine is indicated along this line; for instance, for 2000° F it is 75 percent and for 3000° it is 260 percent. As the amount of cooling fluid required to keep the blades from burning up is increased, the cooling losses cause the gain in power to decrease as indicated by these lines for the two gas temperatures shown. For a coolant-gas flow ratio of 0.07, a nominal value at 2000° F, the loss in power caused by cooling is one-third of the theoretical gain in power which we would obtain if no cooling would be required. For 3000° F, at a coolant-gas flow ratio of 0.15, a nominal value for this temperature, a corresponding loss in power due to cooling would be about 42 percent. The gain in power, even considering the losses, is still appreciable. For 2000° F and a coolant-gas flow ratio of 0.07 the gain in power is 50 percent above present-day operation. For 3000° F and a coolant-gas flow ratio of 0.15, the gain in power is 150 percent above present-day operation. It is desirable to minimize the required coolant flow not only to obtain as much net power as possible but also to achieve more economical operation. This chart and the next two you will see apply directly to turbine-propeller engines. Cooled turbines can also be used to advantage in turbojet engines, especially to reduce the amount of strategic materials used and to obtain high power for emergency operation.

The calculated effect on engine performance of using cooled blades made of alloys with a large percentage of scarce metals is shown in chart 2 (C-24181-A). The turbine-propeller is again considered and theoretical increase in power is again plotted against the coolant-air flow ratio. The water-cooled blade is superior, allowing temperatures of 3000° F to be reached at fairly low amounts of coolant flow. The finned, air-cooled blade also allows 3000° F to be reached, but at a much higher rate of coolant flow, so that the net power obtained is lower than for the water-cooled blade. The net power at this point, however, even with the cooling losses being considered, is still 175 percent above that obtained for the uncooled blade at 1500° F. The use of a plain, hollow blade for air cooling does not appear justified because the low cooling effectiveness of the blade, as demonstrated previously (point to hollow blade), will not allow high temperatures to be reached.

The reduction in strategic blade material which turbine cooling makes possible is indicated by the results shown on chart 3 (C-24181-B). The performance obtained with finned, air-cooled blades installed in a turbine-propeller engine is analyzed. The orange line is carried over from chart 2 where the blades considered were made of high-temperature alloy containing 96 percent strategic materials. The blue line is for the same blade configuration, but with a blade material of alloy steel containing only two percent of strategic materials. The performance is below that shown by the orange line because the blades must be held at lower temperatures requiring more cooling, but the calculations indicate that even with such a material, gas temperatures over 2000° F are possible. The corresponding power gain would be over 50 percent above performance at 1500° F. As shown by the third line, the use of low carbon steel containing no strategic metals in the blade material is not justified for use with air cooling because the amount of cooling air required is so large that the losses prevent any substantial power gains. With water cooling, low carbon steel may have possibilities.

In summary, we believe the predicted performance of cooled turbine engines, which includes cooling losses, is of such promise and the design procedures are of sufficient accuracy that the fabrication of such turbines for prototype engines is feasible. Much work and research effort is still required to obtain data from which more accurate designs can be made.

The prediction of the performance of cooled turbines involves many factors, one of which is the amount of coolant required to prevent the blades from burning up at a given hot-gas temperature. This further involves the accurate prediction of the amount of heat that the hot gas gives up to the blades. The next speaker, Mr. Rossbach, will discuss some methods and techniques used in experimental cooling research to obtain such heat-transfer data and will present some typical results.

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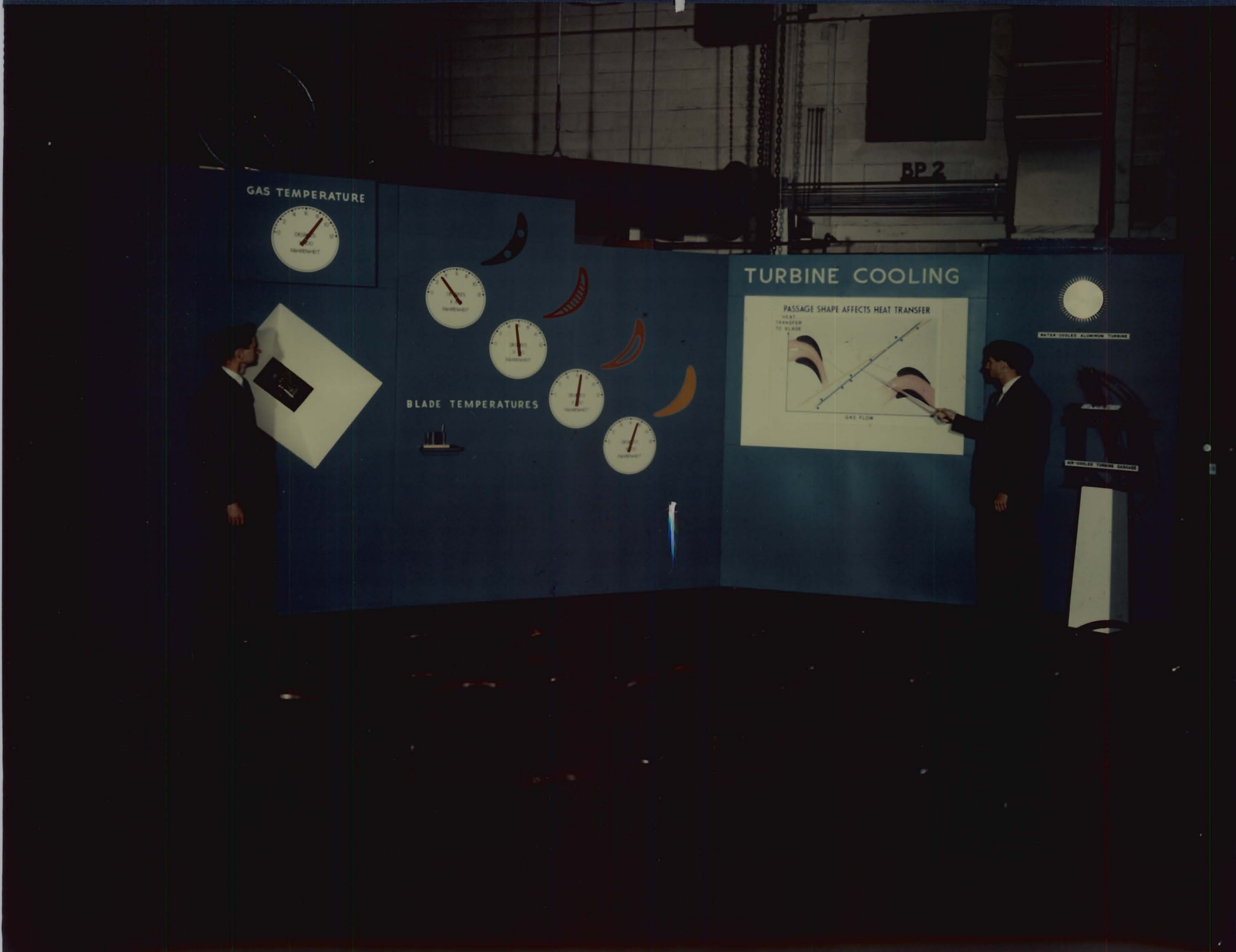
BP 2
GAS TEMPERATURE
BLADE TEMPERATURES
TURBINE COOLING
PASSAGE SHAPE AFFECTS HEAT TRANSFER
HEAT TRANSFER TO BLADE
GAS FLOW


GAS TEMPERATURE
FAHRENHEIT
BLADE TEMPERATURES
TURBINE COOLING
COOLING METHOD AFFECTS POWER
THEOR. POWER GAIN %
3000 °F
LIQUID-COOLED
3000 °F GAS
2000 °F
AIR-COOLED
1500 °F
AIR-COOLED
COOLANT-GAS FLOW RATIO
WATER-COOLED ALUMINUM TURBINE
AIR-COOLED TURBINE CASCADE
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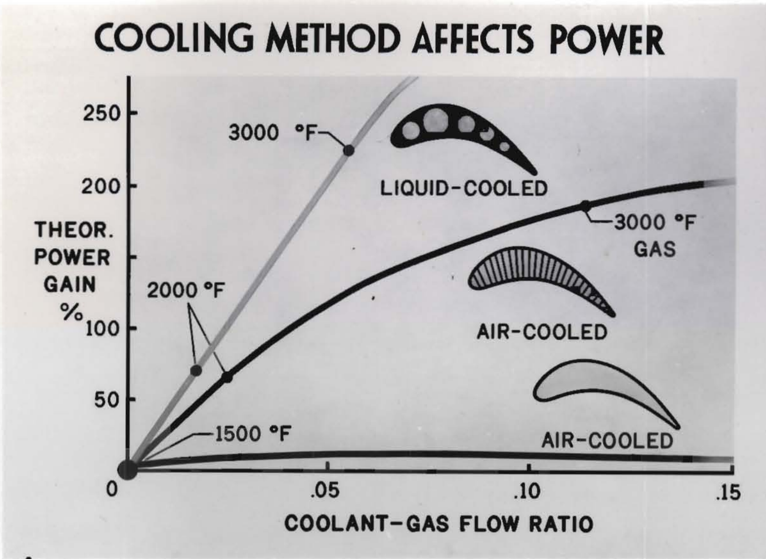

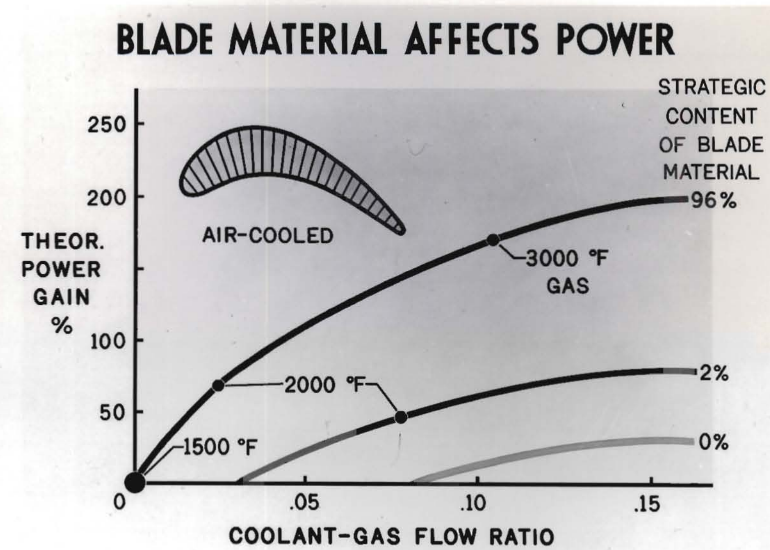

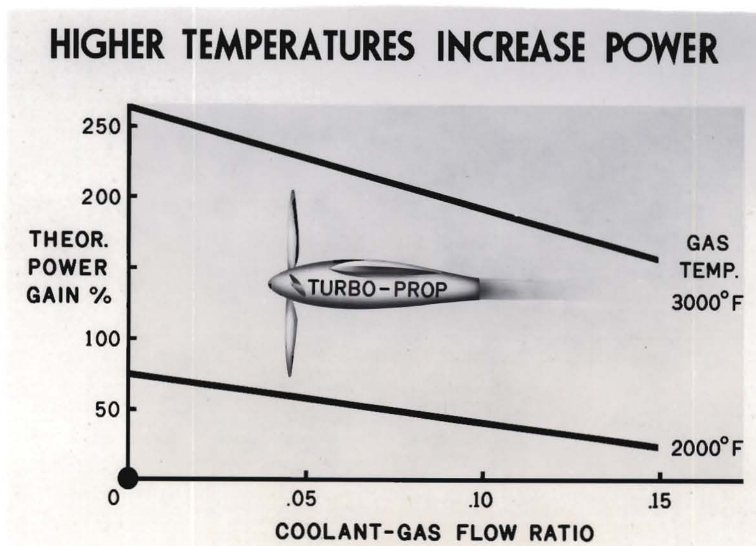

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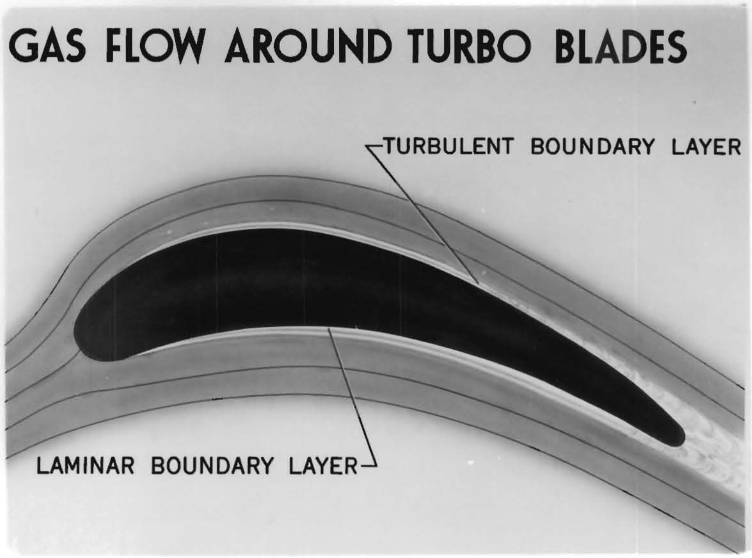
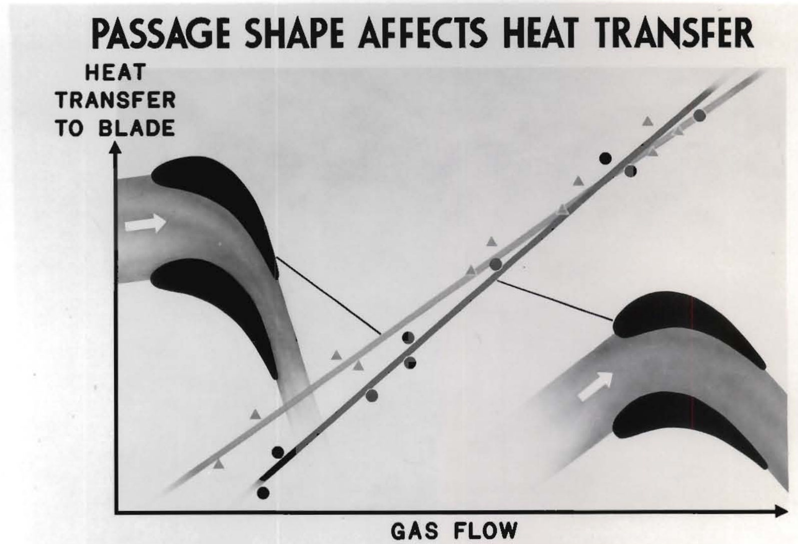
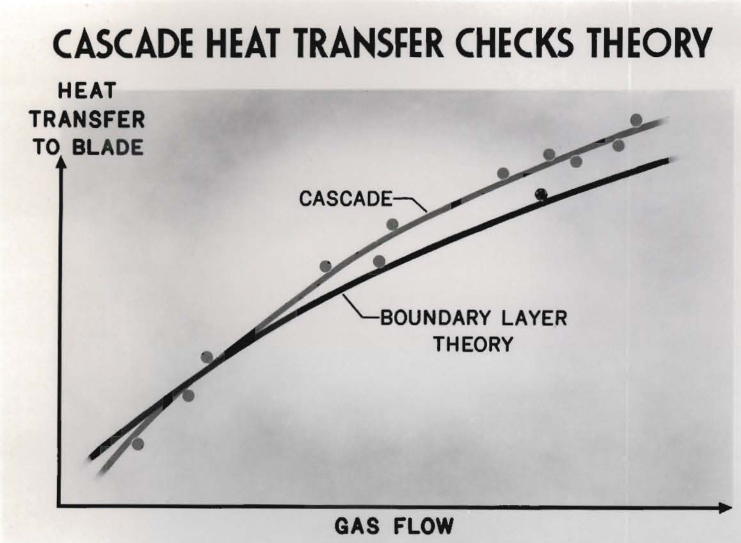
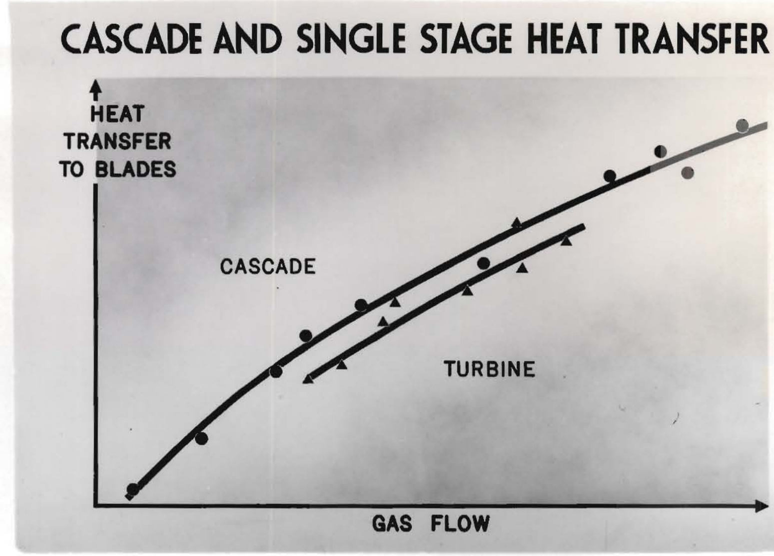
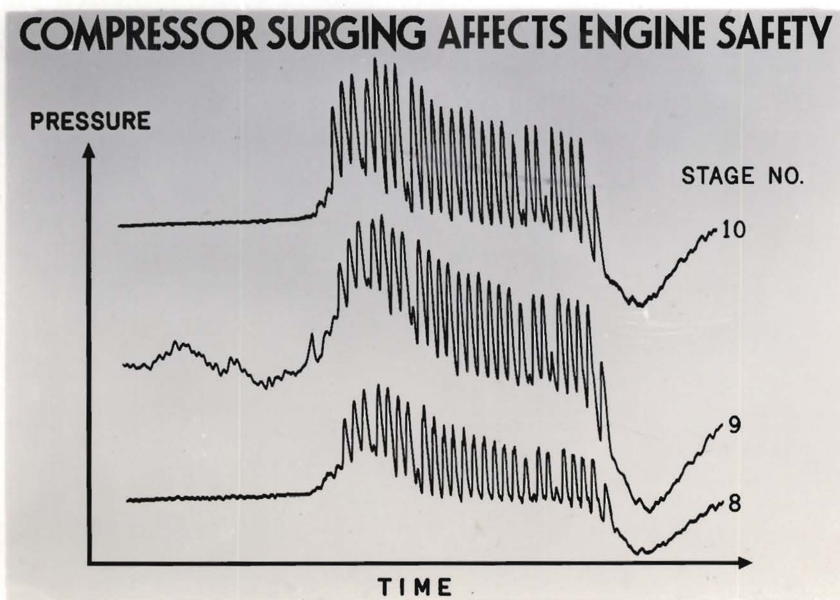

GAS FLOW AROUND TURBO BLADES
TURBULENT BOUNDARY LAYER
LAMINAR BOUNDARY LAYER


PASSAGE SHAPE AFFECTS HEAT TRANSFER
HEAT TRANSFER TO BLADE
GAS FLOW







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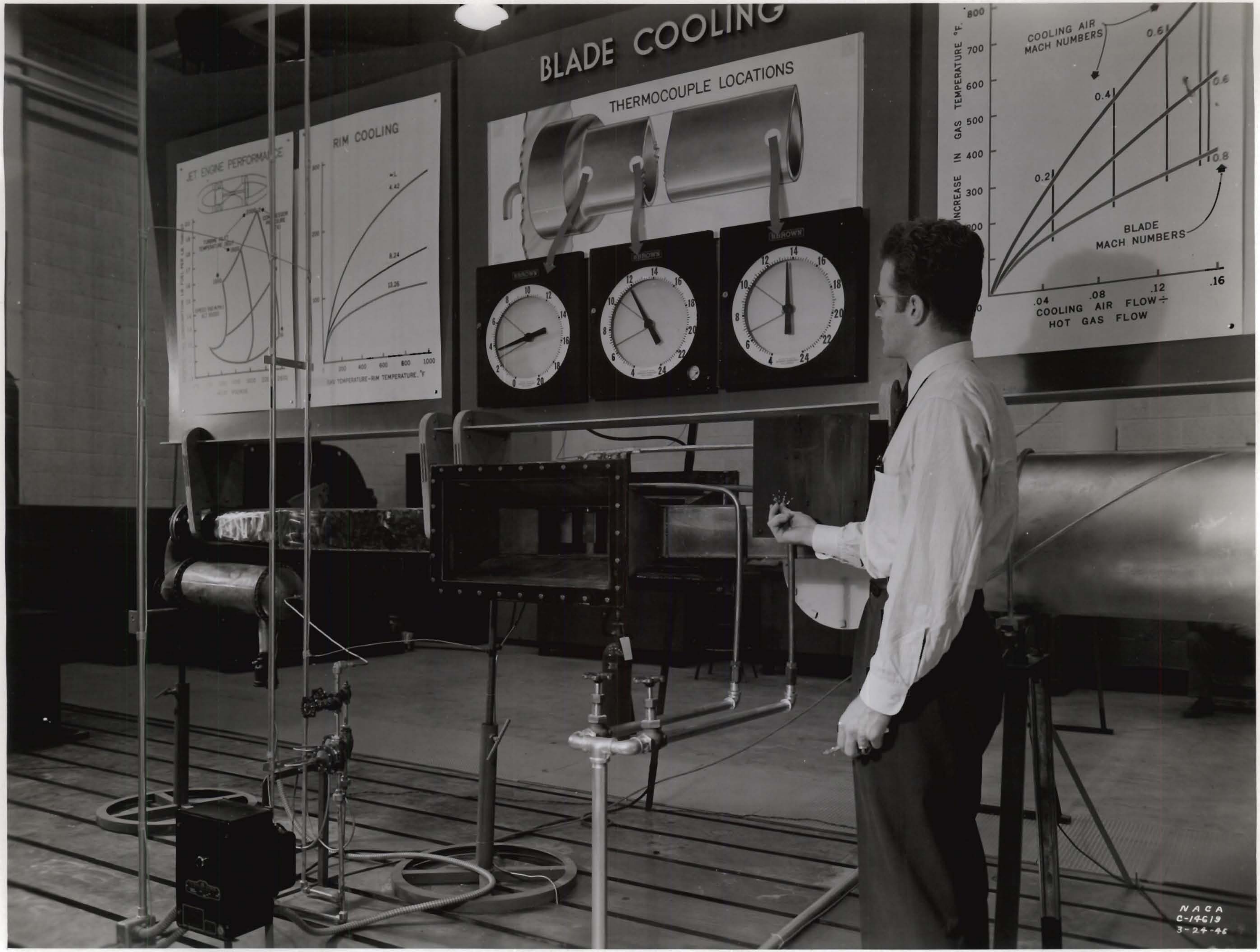

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