PROPELLERS

by

12-Foot Pressure Tunnel

Part I

Prior to the successful development of the jet engine, the propeller had long been the almost universal medium for conversion of the energy from the airplane engine to useful thrust. With the advent of jet-propulsion, interest in propellers became limited to their application to relatively slow-flying airplanes. However, recent improvements in propeller efficiency at high subsonic speeds and the successful development of the turboprop engine have resulted in increased interest in the propeller as a means of propulsion at flight speeds approaching the speed of sound. The turboprop engine is a power plant in which the high energy exhaust gases of a turbojet engine are used to drive a turbine producing shaft horsepower for a propeller. Such an engine offers efficient utilization of fuel over a wide range of flight speeds. It is light and compact and can be made to produce large shaft horsepowers. When combined with an efficient propeller and airframe, the range capabilities of the turboprop installation at high speeds make it well suited for many military and commercial applications. The problem confronting the aerodynamicist, then, is the design of a propeller which can efficiently convert the shaft horsepower available from this new engine to useful thrust at flight speeds approaching the speed of sound.

Since the tip speed of a propeller is a combination of the flight speed and its speed due to rotation, it is obvious that the propeller blade sections or elements are subjected to much higher relative velocities than is the remainder of the airplane. Up until the last few years, losses in efficiency due to compression of the air as the speed of sound is approached have been avoided by operating propellers at lower rotational speeds as the design flight speed increased, so that no part of the blade would be at a velocity greater than the speed of sound. This limitation led to a vicious circle as the flight speeds and power available from the engine increased _ absorbing the higher power required a propeller of larger diameter; the larger diameter necessitated a further reduction in the rotational speed; at the reduced rotational speed the propeller would no longer absorb the available power and still produce thrust unless its diameter was again increased; and so, on and on. It became evident that a complete change in design philosophy would have to be adopted if the propeller was to compete with the jet engine at forward speeds above four or five hundred miles an hour. This has resulted in the so-called supersonic propeller, all sections of which are permitted to operate at supersonic velocities through increased rotational speeds, even though the airplane speed is less than the speed of sound. By permitting the rotational speed of the propeller to increase, it is now possible to utilize large shaft horsepowers with a propeller of comparatively small diameter. Successful design of such a propeller entailed a reassessment of the relative importance of certain factors affecting propeller efficiency in order to minimize the losses associated with the compressibility of air at these supersonic blade speeds. One of the factors involved is shown on this first chart, which presents the variation of the section lift-drag ratio with blade Mach number for blade thickness ratios of 3, 5, and 8 percent. The lift-drag ratio provides an indication of the relative efficiency of blade sections. In the lower speed range, represented by the solid lines, the data were obtained by the integration of pressure distributions on the blades of operating propellers, a type of test recently developed by the NACA for obtaining the aerodynamic characteristics of blade sections at transonic and supersonic speeds. For the higher speeds, indicated by the dash lines, the values were determined from theoretical considerations. It is noted that as the velocity past the propeller blade section increases, the lift-drag ratio remains essentially constant up to a certain critical speed and then decreases abruptly with further increase in Mach number. However, once the section attains a supersonic speed the lift-drag ratio does not change materially with further increase in speed, but is much smaller than at low speeds. While the differences in lift-drag ratio resulting from blade thickness changes do not appear to be large at supersonic speeds, the percentage differences are very large A reduction of thickness from 8 to 3 percent increases the lift-drag ratio approximately 100 percent. These results clearly indicate that if propeller blade sections are to be operated at velocities greater than the speed of sound the most satisfactory lift-drag ratios will be obtained with sections having the minimum blade-thickness ratios permitted by structural requirements.

Continuing now with the factors involved in the assessment of the supersonic propeller, I would like to refer to this next chart in order to elaborate somewhat on the role of the lift-drag ratio and also to explain the concept of pitch angle, the angle which results from the combination of the flight speed and the speed due to rotation. Shown on the upper part of the chart are the effects of the two variables, lift-drag ratio and pitch angle, which uniquely determine propeller blade-element efficiency. Curves of blade-element efficiency as a function of pitch angle are shown for section lift-drag ratios of 5, 10, 20, and 100. It is noted that if the lift drag ratio is greater than 20, the element efficiency is little affected by large changes in lift-drag ratio and is relatively independent of the pitch angle in the range between 20° and 70°. As the lift-drag ratio decreases below 20, it is noted that the efficiency decreases rapidly with reduction in lift-drag ratio and becomes more sensitive to changes in the pitch angle, decreasing more rapidly as the pitch angle is either increased or decreased from an optimum value. For a propeller designed for flight at a Mach number less than about 0.7 it is possible to keep all sections of the blade operating below the critical speed and thus attain a lift-drag ratio of the order of 20. Such a flight condition is indicated as case 1 on the lower left of the chart. For this case, the blade thickness is 6 percent of the chord and the pitch angle is 55°. The blade-element efficiency is about 90 percent as indicated on the element efficiency curve.

Now, proceeding to case 2 we assume that this same conventional propeller is to be operated at a flight Mach number of 0.9. Even though we continue to operate the propeller at the lowest possible rotational speed, resulting in a pitch-angle of 65°, we find that the blade sections are at the speed of sound. The lift-drag ratio, then, is only about 5 as a result of compressibility effects and the blade element efficiency is only 52 percent.

At this point we depart from the conventional procedure involving limitation of the tip speed in favor of an increase in the rotational speed so that the blade velocity is supersonic. Such a supersonic propeller is illustrated as case 3, again at a flight Mach number of 0.9. Note that the increased rotational speed results in a pitch angle near the optimum for best blade element efficiency. Furthermore, the increase in rotational speed has permitted us to decrease the diameter, for the same horsepower, and thus decrease the thickness of the blade. The section lift-drag ratio is then about 10, the increase over case 2 being the result of decreasing the blade thickness. The blade element efficiency is 82 percent as shown at point 3. Thus, by increasing the rotational speed, decreasing the propeller diameter, decreasing the propeller blade-thickness, and operating at optimum pitch angle, the element efficiency has been increased 30 percent. This then, is the design philosophy behind the supersonic propeller.

I now wish to introduce Mr. _______ who will discuss some of the results obtained by the NACA from research on propellers of this type and also point out some of the problems associated with their application.

PART II

During the last two years, NACA propeller research has been directed largely toward the improvement of propeller efficiency in the speed range corresponding to Mach numbers between 0.7 and 1.0. How well this effort has succeeded can be judged from this next chart. Shown in this chart is the effect of Mach number on the propulsive efficiency of a conventional propeller, a supersonic propeller, and a modern turbojet. The propeller efficiencies shown here were obtained experimentally from models in the Langley 8-foot high-speed wind tunnel. The conventional propeller illustrated is representative of a design which, at the time it was developed, embodied every refinement in blade sections, blade plan form, and advance ratio which earlier research had indicated to be desirable. Today, that type of propeller is still superior to more recent propellers at forward Mach numbers less than about 0.65. At higher speeds, the supersonic propeller shows large improvements in performance.

These sketches illustrate the decrease in propeller diameter made possible by recent developments. For a 4-blade propeller designed for 5200 horsepower at a flight Mach number of 0.9, and an altitude of 40,000 feet, a conventional high-speed design would require a propeller about 25 feet in diameter; for the same flight conditions the supersonic propeller would be only about 12 feet in diameter, and would produce nearly 30 percent more thrust.

Two years ago the propulsive efficiency of a turbojet exceeded that of the best propeller at a flight Mach number as low as 0.82. At that time the propeller was not even considered for use at speeds faster than about 500 miles per hour. With the data recently obtained from tests of the supersonic propeller, the indications are that the efficiency can be maintained at a value higher than for a turbojet at flight speeds up to the speed of sound. This improvement in propeller efficiency at the higher Mach numbers makes it necessary to readjust our thinking with regard to the maximum speed at which a gain in over-all performance can be expected by using a turbo-prop as compared to a turbo-jet. The range of an airplane is determined by the propulsive efficiency, the power-plant weight, the fuel consumption, and the airplane lift-drag ratio. Results of calculations comparing the range capabilities of large aircraft powered with turbo-props and with turbojets indicate that for flight at Mach numbers up to at least 0.90, the range of an airplane powered with turbo-props is greater than that of the same airplane powered with turbojets. Conversely, when the range of an aircraft design is specified, then at flight Mach numbers up to 0.90, the requirement will be met only with a jet aircraft of considerably greater weight and size than for a corresponding turbo-prop aircraft.

In the aerodynamic studies leading to the development of the supersonic propeller, the trend toward the use of very thin blades was foreseen. Because it was realized that these thin blades would be particularly susceptible to vibration and flutter, the NACA, during the past two years, has increased its efforts to gain an understanding and solution of these problems.

Propeller vibration is a problem of great concern to both the aircraft designer and the propeller designer and was cited at previous NACA inspections. Since that time, research has been conducted at both Ames and Langley in order to gain a better understanding of these vibratory stresses. Shown at the top of this next chart is a photograph of a twin-engine airplane mounted in the Ames 40- by 80-foot wind tunnel and instrumented for propeller vibration studies. The propeller vibratory stresses were measured by means of strain gages located along the blade. The instrument behind the propeller was used in determining the propeller thrust.

On the bottom of the chart is a comparison of the calculated and measured vibratory stresses due to an angle of attack of the propeller shaft of 8°. Good agreement between the measured and computed values of vibratory stress may be noted except in the region of maximum stress. The slight disagreement shown here is believed to be due to local deformation of the hollow steel propellers.

The results of these investigations at Ames and of a similar investigation of an isolated propeller at Langley have indicated conclusively that the fundamentals of the problem of vibratory stresses caused by propeller angle of attack are understood and these stresses can be accurately calculated if the speed and direction of the flow at the propeller is known. Additional work is underway on methods of accurately predicting the field of flow for wing-nacelle-fuselage combinations.

The vibration problems which we have discussed and problems associated with propeller flutter are not peculiar to the supersonic propeller but are amplified by the thinness of blades required if efficient operation is to be achieved near the speed of sound. The magnitude of the vibratory and flutter stresses encountered are such that they play a dominant role in the determination of the minimum blade thickness which can be used in the supersonic propeller. Both theoretical and experimental studies by the NACA of propeller vibration and flutter are continuing.

I now wish to introduce Mr. ____________ who will discuss the problem of air inlets for the turbo-prop engine.

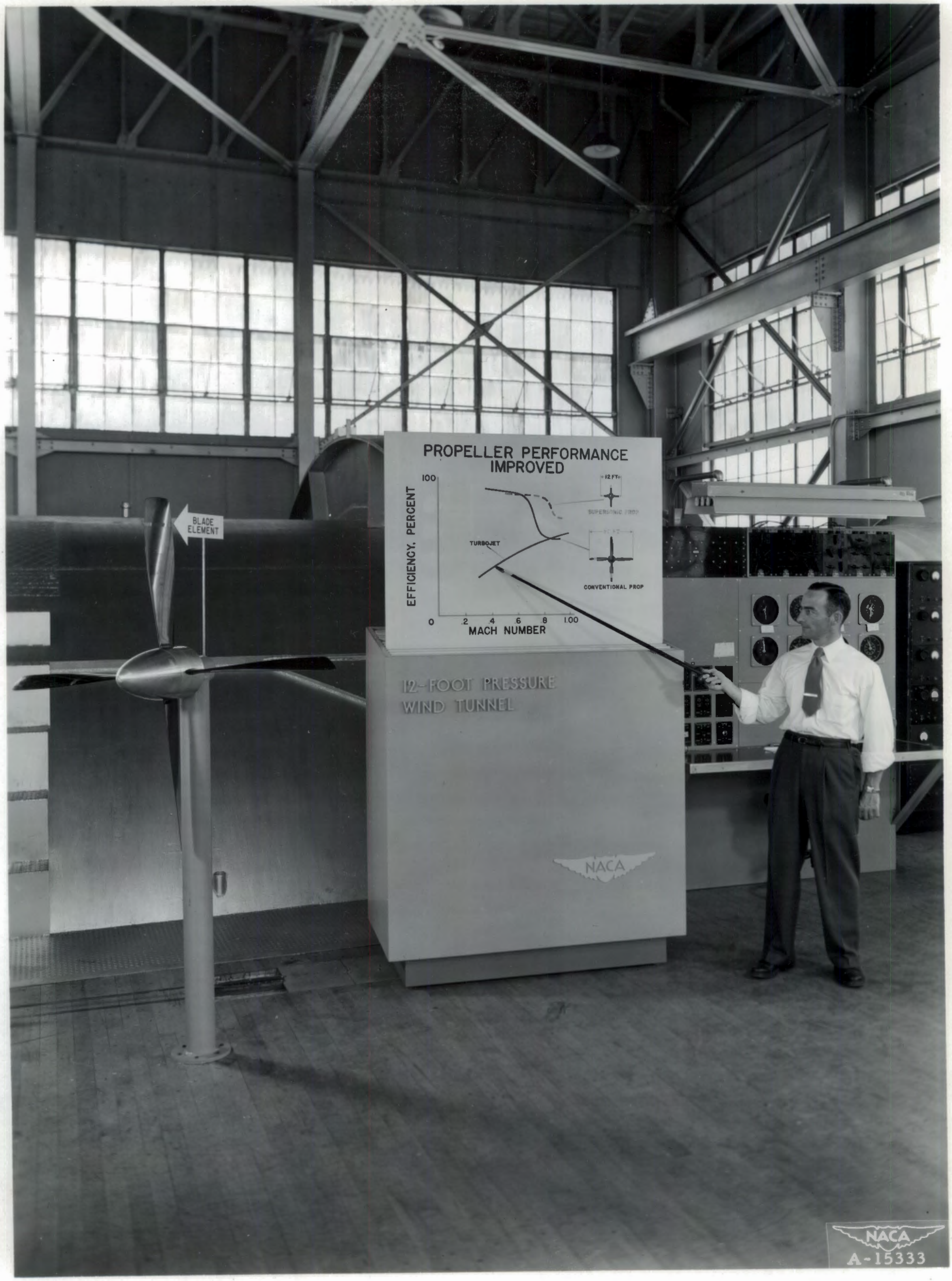
PART III

In order to exploit fully the long-range potentialities of the turbopropeller aircraft which were discussed by Mr _______, it is necessary that large quantities of air be delivered efficiently to the engine. At low altitudes, a modern turbine engine requires as much as 3 tons of air every minute. It is extremely important that this air be delivered to the engine with the maximum possible efficiency. Any energy losses in the entering air are reflected in reduced engine power and increased fuel consumption with concomitant reduction in airplane range. This chart depicts three types of air inlets for turbo-propeller installations which are currently being studied at the Ames 12-foot wind tunnel. The inlet on the upper left is an NACA E-type cowl, an annular inlet which rotates with the propeller. Streamline fairings over the thick blade shanks inside of the cowl reduce entrance losses associated with flow over the inner portions of the blades. The efficiency of the internal flow with a well-designed inlet of this type is extremely high; the inlet losses being less than 2 percent at forward Mach numbers approaching 0.90. The inlet shown on the right is the conventional NACA D-cowl. Low speed tests have shown that by using thin propeller blade shanks and properly proportioning the spinner and cowl, entrance losses with this type of an inlet can be maintained at a low value. Further investigations are underway to determine the magnitude of the internal and external losses at high subsonic speeds. The inlet shown on the lower part of the chart is a scoop type. An inlet of this type may often be used to advantage on dual or coupled turbine engines. High efficiency can be attained with this type of inlet if thin propeller shanks, properly alined, and aerodynamically clean propeller-spinner junctures are used. Research on air inlets for turbines behind operating propellers is continuing in an effort to increase the efficiency of air induction and to decrease the total airplane drag.

We have shown some of the results of recent NACA research on propeller efficiency and on vibration problems associated with the attainment of high efficiency at high speeds. A few years ago, it was felt that propeller-driven airplanes could not compete with turbojet aircraft at Mach numbers greater than about 0.80. By the use of very thin propeller blades operating at blade speeds which are supersonic, it has been found possible to increase propeller efficiencies over those attained with conventional propellers by as much as 30 percent in the range of forward speeds corresponding to Mach numbers between 0.70 and 0.92. As a result of these recent developments, the propeller will now be seriously considered for airplanes designed to fly at Mach numbers up to at least 0.90.

Both theoretical and experimental research on propellers is continuing. This model propeller is one of several which are scheduled for tests in the 12-foot pressure wind tunnel and other facilities of the NACA. While the efficiency of a supersonic propeller is now about 75 percent at a Mach number of 0.92, there is reason to believe that the efficiency in this speed range can be improved by further refinement of design.

The supersonic propeller has now reached a stage of development where it is ready for experimental flight research. Prior to its application to long range aircraft, problems associated with its vibration and flutter must be more thoroughly investigated. This concluses the 12-foot program. Thank you for your attention.



Display for Presentation of "Propellers" by 12-Foot Pressure Tunnel

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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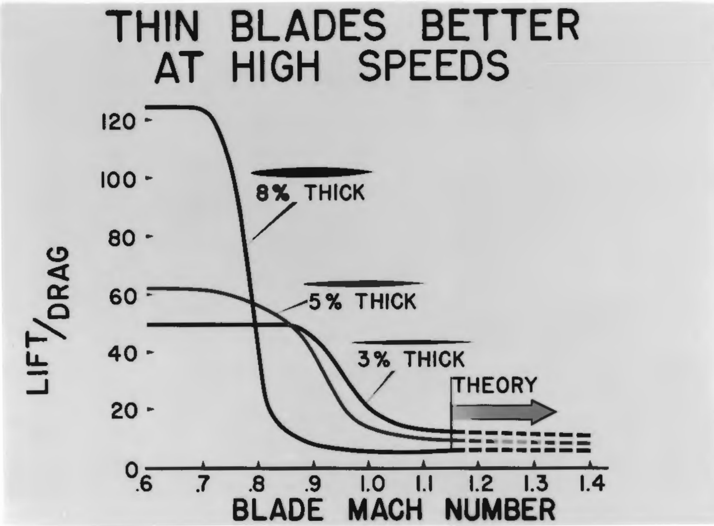

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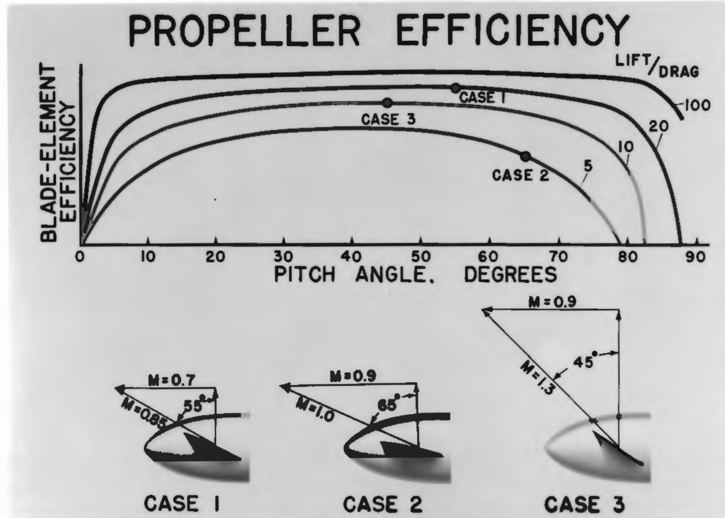

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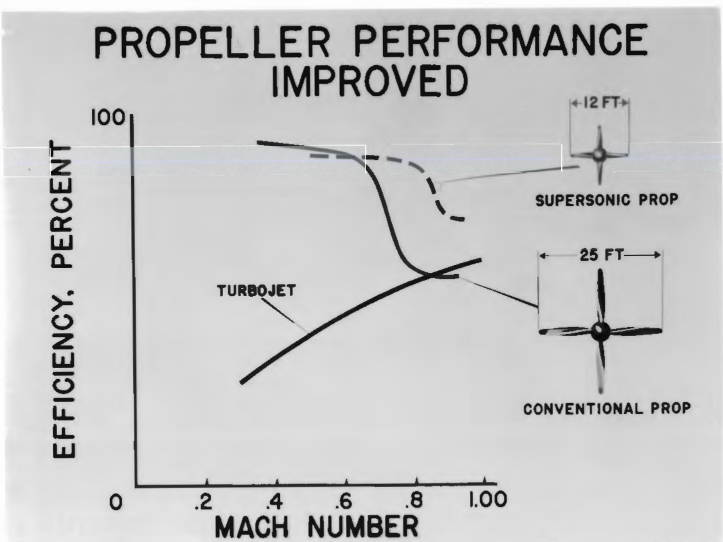

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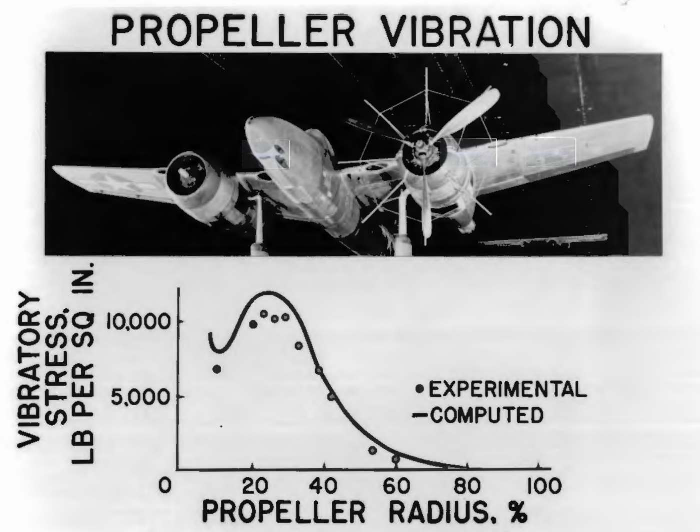

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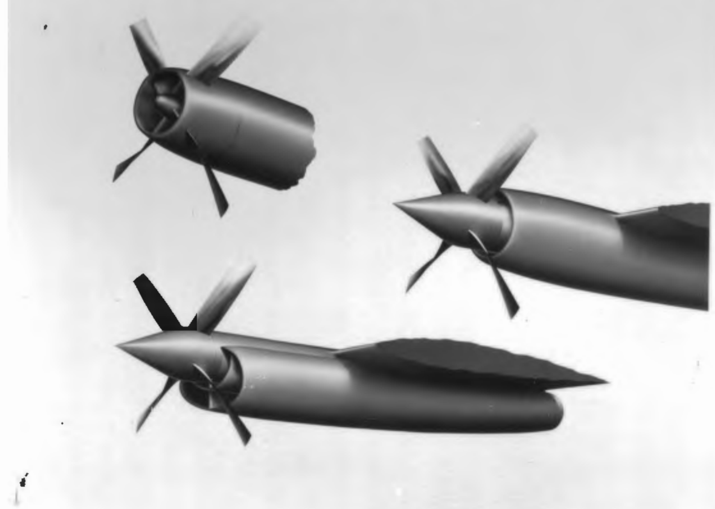
PROPELLER-INLET COMBINATIONS



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