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IMPACT OF ADVANCED PROPELLER TECHNOLOGY ON AIRCRAFT/MISSION CHARACTERISTICS OF SEVERAL GENERAL AVIATION AIRCRAFT

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16. Abstract

Studies of several General Aviation aircraft have indicated that the application of advanced technologies to General Aviation propellers can reduce fuel consumption in future aircraft by a significant amount. Propeller blade weight reductions achieved through the use of composites, propeller efficiency and noise improvements achieved through the use of advanced concepts and improved propeller analytical design methods result in aircraft with lower operating cost, acquisition cost and gross weight.

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SUMMARY

This study effort was conducted to generate information necessary for the Government to formulate the most effective technology program for General Aviation propellers. Advanced technologies and their associated benefits were identified as well as their technical risks and required research programs.

The study began with the selection of baseline aircraft and propellers. A preliminiary analysis determined the effect of selected advanced propeller technologies on propeller criteria of merit, i.e. performance, weight, noise and cost.

The study of a wide range of propeller design variables and advanced technologies has indicated that the potential exists for propeller performance improvements and weight reductions meeting consistently more stringent regulatory noise levels.

Advanced technology propellers of lighter weight and better performance with lower noise and greater safety margin are possible because the blades would be constructed from composite materials. Screening appropriate materials, blade manufacturing techniques, and root end concepts was accomplished. Comments were made on areas to be investigated to assure structural integrity.

The impact of each technology element studied and the effect of variations of propeller design parameters was quantified in terms of the mission characteristics of each aircraft. A trade-off analysis was then performed and an "optimum" propeller defined for each aircraft. The benefits of the advanced technology propellers were then identified relative to current metal propellers in terms of fuel burned, operating cost, acquisition cost, and aircraft gross weight.

Advanced technology propellers increased cruise efficiency about 5 to 9 percent, lowered fuel consumption 8 to 18 percent, and reduced aircraft operating cost 5 to 6 percent while meeting the FAR Part 36 noise constraint.

INTRODUCTION

To insure that USA built General Aviation aircraft remain competitive and dominant in the world market place, support energy conservation needs, and meet environmental requirements, a renewed research effort is needed to improve the technology level of General Aviation (G.A.) propellers. Current technology for these propellers is based for the most part on research conducted during the World War II era or shortly thereafter. Few advances have been made since this time as research was terminated by NACA (NASA) in the early 1950's. Current G.A. propellers are, in general, designed using limited analytical capabilities. These techniques vary from table look-up methods to Goldstein strip analysis theory. The design process also relies heavily on many years of design experience, empirical correlations and experimental verification.

Improved materials and fabrication technology, and advanced computer analysis tools, in combination with new propeller concepts will be the cornerstones leading to future, advanced, energy-efficient G.A. propellers. Preliminary indications are that suitable advanced technology designs and fabrication techniques could be developed to produce improved G.A. propellers that utilize composite materials in the structure of the blade assemblies. In addition, new concepts like blade sweep, aero-acoustic airfoils and tip devices such as proplets are being investigated. Since these concepts show potential for performance benefits and lower noise they may be included in future advanced propeller designs by taking advantage of the increased structural capabilities of composites. Advanced analysis tools will be needed to more accurately model the aerodynamics, acoustics, aero-elastics, and structural integrity of these new propellers.

A proper blend of these new concepts into a propeller having advanced composite materials and an optimum design using advanced analysis techniques could result in improved propeller performance, lower noise, enhanced safety through improved fatigue life, and significant propeller weight reductions. The result would be a lower gross weight aircraft having reduced fuel consumption with lower operating and acquisition cost.

Under NASA-Lewis Research Center Contract NAS3-21719, McCauley Accessory Division of Cessna Aircraft Company has conducted a study to evaluate the impact of advanced propeller technologies appropriate for General Aviation aircraft. This study identified applicable advanced technologies and assessed their potential costs and benefits. The impact of an optimum combination of these technologies on aircraft fuel consumption, weight, and cost was evaluated during the mission analysis task. A recommended research program to develop these technologies was prepared, and it is hoped that NASA resources can be channeled into the technology areas showing the greatest potential benefits.

The general tasks performed in this study are shown in Figure 1, and the various sub-contractors who contributed to this study and their areas of expertise are shown in Figure 2.

U. S. customary units were used in this study. These units were converted to the International System of Units for presentation in this report.

DESCRIPTION OF STUDY

The baseline aircraft selected for this study were chosen to be typical of current General Aviation (G.A.) aircraft types and encompass the full range of G.A. aircraft capabilities from low speed, low power to higher speed, higher power aircraft. The selected aircraft include four in the two to eight place, single and twin reciprocating engine class; a twin engine turboprop powered aircraft; an agricultural applications aircraft and a nineteen (19) passenger turboprop commuter aircraft. The specific aircraft chosen as baselines are illustrated in Fig. 3 and their power and cruise speeds are presented in Table 1. The nineteen passenger commuter is not an existing aircraft like the others, but rather a study aircraft proposed by the Cessna Aircraft Company for the Small Transport Aircraft Technology (STAT) study (ref. 1).

The baseline propellers used in this study are the current production models in use on each of the selected existing aircraft. For the commuter aircraft, a propeller was selected which could be designed for that aircraft using current G.A. propeller technology. Table 2 presents the characteristics of each baseline propeller.

The advanced propeller technologies considered for the study were those with the potential for improving aircraft characteristics; that is, fuel burned, operating cost, acquisition cost, and gross weight. The selected technology elements include those felt to have any potential whatsoever based on an evaluation of current propeller loss mechanisms and deficiencies, McCauley experience, experience of other propeller manufacturers, and available literature.

Initially, the technology elements were evaluated in terms of their ability to increase propeller performance and/or lower noise. The newer concepts evaluated were NASA proplets, blade sweep and advanced technology airfoils. Also evaluated were improved blade surface finish expected from composite blades and improvements in propeller/nacelle integration and spinner/blade shank blending. In addition, the initial evaluation included variations of various propeller parameters to allow for their inclusion in the trade-off and optimization procedures later in the study.

The propeller elements evaluated included variations in power loading (i.e. diameter), blade loading distribution, activity factor, number of blades, blade thickness and tip speed.

Composite blade materials were also evaluated in this study. Since composite propeller blades are structurally superior to current aluminum blades, advanced technology elements such as sweep, NASA proplets, low activity factor and thin blade sections may be entirely feasible in an advanced design propeller. Such a propeller is illustrated in Figure 4 along with the advanced technology concepts that it might incorporate.

Composite materials were screened and four were selected for evaluation: E-Glass, S-Glass, Kevlar, and Graphite. These were evaluated in terms of strength, cost and weight. Composite propeller design methods and manufacturing costs were also surveyed.

A trade-off analysis of the propeller design parameters was then performed to determine an "optimum propeller" for each aircraft studied. The "optimum propeller" is the combination of propeller size, design parameters, and advanced technologies which in the opinion of McCauley represents the most suitable propeller for each application. The trade-off analysis was performed using an optimization procedure that allowed a step-wise evaluation of each propeller variable. The effect of each variable on aircraft/mission characteristics was evaluated in terms of its effect on propeller performance, noise, structure, materials, weight and cost. The optimizations were carried out by using a mission analysis procedure that quantified fuel burned, operating cost, acquisition cost, and aircraft gross weight. These evaluations were made by resizing the aircraft so that improvements in performance and weight, for example, would yield smaller airframes. Aircraft payload, range and speed were held constant. For each aircraft, the benefits of the "optimum propeller," relative to the current metal General Aviation propeller, were determined for two noise constraints; for FAR Part 36 noise regulations (or the actual noise level, if less), and for FAR Part 36-5dB(A).

RESULTS AND DISCUSSION

Technology Assessment

Performance Considerations

There are three basic loss mechanisms which affect propeller performance. These are induced (or ideal) losses, blade drag losses, and interference losses. Interference losses include any adverse flow interactions between the propeller and nacelle or airframe and any between the blades and spinner. In this study the various technology elements with the potential for reducing these losses and improving propeller performance were identified and evaluated. These loss mechanisms and the references used to evaluate them are listed in Table 3.

Some of these elements could, with unrestricted application, dramatically improve propeller performance. However, the use of any of these elements is generally limited by practical constraints and the elements effect on the other important criteria of merit such as noise, weight, and structural integrity.

The effect of the technology elements on propeller performance are given in Figures 5 through 12. Figure 5 shows the effect of power loading and number of blades on induced efficiency at a tip speed of 900 fps (typical of current technology) covering the 50-300 knots airspeed range with 2-8 and an infinite number of blades. Figure 6 shows the effect of power loading and tip speed on induced efficiency, covering the same number of blades and airspeed ranges. These figures show a consistent trend over the entire operating range; namely, that induced efficiency is improved by reducing power loading, increasing the number of blades, and increasing tip speed (ref. 2).

The efficiency gain achieved by adding propeller blades is due to a reduction in the tip losses (Fig. 5). NASA proplets (Fig. 4) are a new technology concept that can also be used to reduce this blade tip loss without incurring the added propeller blade weight. The amount of the tip loss reduction is a function of the proplet span (Fig. 7). The proplets would be designed to operate with a radial inward force that includes a component in the thrust direction to improve efficiency. Theoretical and experimental work to evaluate these devices for NASA is underway by Dr. John Sullivan of Purdue University (ref. 3).

An example of reducing the profile losses and thus increasing efficiency by increasing blade sweep is shown in Fig. 8. For propellers that operate with a sufficiently high tip Mach number, the outer portion of the blade can be well into drag rise. Sweep can be used to reduce the effective Mach number in this region and reduce compressibility losses. As will be discussed later, sweep can also be used to reduce noise. The improvement in performance possible through the use of advanced airfoils to improve the blade lift to drag ratio turns out to be relatively small. It is conservatively estimated that about .5% efficiency improvement is feasible. The effect of reductions in blade thickness on propeller efficiency were studied by utilizing the McCauley Strip Analysis Computer Program (ref. 4,5). The results are presented in Fig. 9 where the blade thickness reductions are shown in terms of thickness ratio reductions at the 75 percent blade radius station. The efficiency gains shown in the figure are a result of the lower profile drag of thinner blade sections.

Surface roughness, especially near the airfoil leading edge, has a significant effect on drag characteristics, in that drag increases progressively with increasing surface roughness. Surface roughness has its most pronounced effect at section angles of attack near stall on both the upper and lower airfoil surfaces. Also, roughness has its most degrading effect on drag the closer to the leading edge it occurs.

The use of composites will allow blades to be produced uniformly with better surface finish than possible with blades produced from aluminum forgings. Also, through the use of composite blade materials and leading edge erosion strips, maintainability of blade shapes and a more lasting surface finish in service can be realized. A procedure for assessing the effect of airfoil surface finish on drag was found from reference 6. From this reference, a 10% drag difference was determined between the rough and smooth airfoil which resulted in approximately .5% section efficiency difference.

For a given operating condition and propeller diameter, a total activity factor exists which minimizes profile losses. From data extracted from reference 7, empirical relationships were determined, checked out for accuracy, and presented in Fig. 10. Often a non-optimum activity factor is used with current technology propellers to enable the use of an available blade forging over a diameter range.

It is a well known fact that the presence of a body aft of the propeller affects the flow field entering the propeller disk primarily in the inboard sections. The nacelle or cowling and spinner configurations used on General Aviation aircraft today have not been designed with propeller/nacelle integration in mind. They are desigred to be minimum in size to house the engine and propeller hub, but do not have optimum area and streamlined shapes. Therefore, the potential for improvement was felt to be significant and it was the purpose of this study to address this area and to quantify the potential improvements possible.

Several aircraft were chosen to cover the range of body blockage geometries typical of General Aviation aircraft. These include typical single engine reciprocating installations which have body to propeller diameter ratios in the .4 to .54 range and typical twin engine turbo-prop installations which have blockage ratios in the .23 to .38 range.

In order to determine the inflow velocity distribution, the Douglas-Neumann Potential Flow Program (ref. 8) was used at the typical cruise velocities of each aircraft studied. Spinner and nacelle or cowling contours were circumferentially averaged to obtain a single plane profile.

The effect of inflow velocity distribution on propeller propulsive efficiency was studied by comparing the determined inflow velocity distribution with the idealized case, i.e. uniform inflow using the McCauley strip analysis program (ref. 4, 5). Looking at the differences between apparent and effective efficiencies as influenced by body blockage, the apparent thrust increases with inflow velocity reductions and unrealistic efficiencies are calculated. The true efficiency gains represent only a portion of the difference between apparent and effective efficiencies. The true potential gains are the free stream efficiency of the isolated propeller properly twisted minus the effective efficiency of the propeller properly twisted for retarded inflow.

Efficiency gains from minimization of interference losses through reduction in body to propeller diameter ratio are shown in Fig. 11.

Tests at Lewis Research Center have indicated that the drag associated with a round shank propeller can be quite high (ref. 9). The high drag is a result of two factors. The first factor is the large interference drag between the round shank and the spinner surface. This is the largest portion of the high drag. The second factor is the drag of the round shape itself. By maintaining a reasonable airfoil shape down to the spinner surface, a large part of these drag losses can be eliminated. Figure 12 shows the resulting efficiency gains that can be achieved by assuming that 75 percent of the interference drag is eliminated when an airfoil shape replaces the round shank. Some earlier NACA tests on non-G.A. propellers (ref. 10 and 11) have shown large potential efficiency gains by improving the blade geometry in the inboard region. Correlation of these results with empirical loss estimates and the aforementioned wind tunnel tests is reported in reference 9. Future work to better integrate the spinner and blades may offer some additional improvements.

A parametric study was conducted to evaluate the effects of each of the above technology elements (Table 3) on propeller performance for each of the six study aircraft. These results were used in the trade-off and propeller optimization discussed later.

Acoustic Considerations

The primary technology elements affecting acoustics are number of blades, tip speed, thickness ratio, activity factor, sweep, blade loading, airfoil technology level, and proplets.

A list of these technology elements along with the references utilized to evaluate their effect on propeller criteria of merit are shown in Table 4.

Examples of the effects of some of the above technology elements on noise are presented in Figures 13 through 17 and 19. The first three examples, Figures 13-15, show the effect of three elements (blade number, blade sweep, and blade thickness) that have the potential to decrease noise as well as increase performance (Figures 5, 6, 8 and 9). Increasing the number of blades will decrease the loading per blade and concomitantly the blade loading noise. Sweep can reduce propeller noise through partial cancellation of the acoustic pressure signature emanating from the different blade radial locations (ref. 12). Thickness noise reductions are limited by a structural constraint on the achievable minimum blade thickness.

Other technology elements, such as reducing the tip speed (Fig. 16) and moving the peak loading inboard (Fig. 17) will decrease noise, but at the expense of lower performance. Performance penalties resulting from reduced tip speed and moving peak loading inboard are shown in Figs. 6 and 18, respectively.

Activity factor reductions have a direct impact on lowering thickness noise. The effect on overall sound pressure level is as indicated in Fig. 19. Activity factor requirements are primarily dictated by performance. If reduced activity factor is needed for performance optimizing then noise is also reduced, but if the opposite is true then the noise and performance requirements are in conflict.

Because of the high relative velocity at the tip, NASA proplets will have to be carefully integrated into the blade acoustic design to keep the noise from increasing. By sweeping the proplets relative to the rest of the blades, some noise cancelling should be possible. In fact, some initial acoustics analysis work has indicated that swept proplets can be designed without an increase in overall propeller noise (ref. 3). Noise reduction through incorporation of proplets is conservatively estimated to account for about .5 dB(A).

Little is known regarding the potential reductions possible through the use of advanced airfoils. Most experts agree that a small potential exists. About .5 dB(A) is the best estimate currently available.

A parametric study of the above acoustic elements was conducted to obtain data for the trade-off and propeller optimization procedures. The effect of each acoustic technology element on propeller noise was evaluated for four aircraft covering a wide power range as representative of the General Aviation fleet. The four aircraft were the Cessna 172N, Cessna 210M, Cessna 414A and the 19 passenger commuter aircraft. The Cessna A188B was not included in the parametric study since agricultural aircraft are not bound by FAR Part 36. Also, the Cessna 414A aircraft was not included due to funding availability, however, the acoustical sensitivity of the technology elements was inferred from similarities to the other aircraft studied.

Composite Material Considerations

In order to reliably meet the future performance and acoustic requirements of G.A. propellers, consideration should be given to blades that are fabricated from advanced composite materials. Such blades may provide a considerably lower propeller weight and newer fabrication techniques may lower their costs to a level that will make their prices competitive with those of aluminum blades. Advanced filamentary composite materials combine low densities and low notch sensitivity with high strengths and stiffnesses. These characteristics may lead to propellers having not only lighter weight but better performance, lower noise and greater safety margins (Fig. 20). The performance and noise benefits result from a wide design flexibility which allows control of thickness, mass, and stiffness distribution to a degree not possible with metal blades. Tailoring of the composite matrix will allow the designer to vary the radial stiffness distribution and shape the primary bending and torsional modes to the design requirements. Thus, the dynamic and strength characteristics can be optimized to allow the construction of blades with advanced design concepts; for example, a thinner, lower activity factor, swept blade with proplets such as sketched in Figure 4.

Because filamentary materials are only strong in the filament direction, careful consideration must be given to ply orientation and possibly the use of hybridized materials to meet the design requirements. The higher blade deflections resulting from the use of composite materials rather than aluminum must be carefully analyzed in that they can lead to large out of plane deflections and may result in aeroelastic instabilities.

Screening of Materials. - In the present study a range of composite materials were screened to determine the most desirable concepts for advanced propellers. The results pointed to a family of materials including E-Glass, S-Glass, Kevlar and Graphite. These materials are compared in Figure 21 in terms of the weight and cost of a composite propeller blade relative to an aluminum propeller blade. The materials shown in the figure are arranged so that cost increases and weight decreases from left to right. Notice that the manufacturing costs of the composite blades are all about the same so that the total cost variations are primarily due to the changes in material costs. Although the manufacturing costs of the composite blades are higher than those of aluminum blades, the total material costs are lower in many cases because the low material weight of composites more than offsets the higher cost per pound. The total cost of three of the composite blades (E-Glass, S-Glass, and Kevlar) are nearly competitive with the cost of aluminum blades and future improvements in fabrication techniques could make them even more competitive.

The best material choice for the near term use of composite blades appears to be E-Glass (weighing 73 percent of an aluminum blade and costing 20 percent more) and Kevlar (weighing 50 percent and costing 30 percent more). It is obvious from the high cost of Graphite that it would only be used when absolutely necessary to meet high strength needs in advanced propellers. A hybridized composite including small amounts of graphite would be more feasible under most circumstances.

Design Philosophies and Manufacturing Techniques. - The procedure used to design a propeller involves a complex iteration process that attempts to obtain the lowest cost propeller blade which satisfies the aerodynamic, structural and environmental criteria. These criteria are listed in Figure 22 and the iterative process to assure blade structural adequacy is shown in Figure 23. Aerodynamic and environmental criteria invariably complicate satisfying the structural and manufacturing cost criteria. For the most part, it is the detailed trade-offs between structural efficiency and manufacturing cost that dominate the major engineering effort. Cost of manufacturing includes quality risk factors associated with the manufacturing process selected.

The results of a study of composite manufacturing techniques that are applicable to propeller blade construction are described below. Methods of leading edge erosion protection, various forms of composite material construction and different concepts of blade hub retention are presented. The advantages and disadvantages of each method are discussed to indicate the relative merits of each method and show where advances in these methods may be needed for their successful application to blade construction.

Erosion protection on composite blades can be provided by an electroformed nickel or stainless steel cap. Because of the compound curvature of advanced blade configurations, however, an erosion cap might have to be of electroformed nickel. The leading edge radius, twist and planform may preclude the use of simpler stainless steel caps.

Composite blade fabrication can be classified according to the material form used in the process. Three major categories are filament winding, woven fabrics and tape goods.

Filament winding was examined as a fabrication technique. This technique was discarded because the technology of this process is incapable of producing the blade sections which have very small leading and trailing edge radii.

Woven fabrics were considered in a broad sense, but they were eliminated for structural reasons. Woven fabrics of a given material are lower in modulus and strength compared to tape goods. On an equivalent stiffness basis this results in a weight penalty for woven fabrics. Based on these facts, this material form is not competitive with tape goods for a minimum weight blade design.

The manufacturing processes addressed in this section assume the use of tape goods in the form of prepreg materials. Each process is described below along with a summary of the advantages and disadvantages of each.

A concept using precured leading and trailing halves is shown in Figure 24. The blade is hollow and molded in two halves with the split line at the crossply overlap which is on the pitch axis. This overlap location has two advantages. First, it is at the maximum section thickness, which maximizes its contribution to the flapwise stiffness. Second, the overlap contributes the lowest increase in polar moment of inertia. Due to the smaller leading and trailing edge radii of some advanced airfoils, a precured cap is required along the entire trailing edge and sections of the leading edge which are without an erosion cap.

The precured cap is inserted over the uncured layup. The cure of a specific half bonds the cap in place. Once the halves are cured, a precured web is bonded to the trailing edge half. The web acts as a mandrel when bonding the halves together, so that the bond can be pressurized. The two halves are then bonded together over the root end retention fitting. The root end is filament wound and the leading edge erosion cap is bonded to the cured blade.

The advantages of this manufacturing method are: 1) the risk of fiber wrinkles is low because all the surfaces are molded in matched dies; 2) the placement of the fibers is accurate; 3) excess resin is removed assuring an optimum fiber volume; 4) the cured parts can be inspected before final assembly resulting in low total blade scrappage.

The disadvantages of this process are that: 1) the presence of the split lines represent an added cost because dressing is required after final assembly; 2) secondary bonds of primary structure increases labor man hours; 3) bonding the erosion cap as a secondary operation also increases the labor man hours; and 4) solid tip sections add complexity to the tooling and material layup operations.

The second concept investigated involves prepreg material laid up around a precured urethane foam core and is presented in Figure 25. This method has one major curing operation. The leading and trailing edge precured caps are then properly located and the assembly is cured. The erosion cap is bonded to the cured blade and the filament winding is applied to the root end in secondary operations. In this process the foam core must be skinned to provide adequate leading and trailing edge pressure during the cure cycle.

The significant advantage of this process is that there is only one major curing operation. Secondary advantages include the absence of primary structural bonds and dressing of any split lines.

The disadvantages are numerous. There is a greater risk of fiber wrinkles and fiber wash with this process. More hand work of the prepreg material is required to minimize this risk. If defects do occur, final inspection is more costly. The cost of the materials and labor is significant, if an essentially completed blade is scrapped. When the root end mandrel is molded in place, additional tooling to pressurize the composite is required between the foam core and mandrel. This process results in the highest blade weight of the three concepts primarily because of the foam core weight. Higher cured resin content is inherent with this method. This also contributes to the increased weight. In the tip region where the blade sections are thin, the sections must be solid composite for structural integrity. Because of this requirement fiber wrinkles and fiber wash are a distinct possibility. Since there is no foam in these locations it is difficult to accurately locate the material.

The third proposed concept uses precured upper and lower spars, presented in Figure 26. The upper and lower unidirectional spars are separately precured on a crossply skin carrier in matched die tooling. Once cured, the spars are bonded together, along with the root end mandrel, forming an airtight inner chamber. The outer skin is then draped over this spar overlapping at the pitch axis. The precured leading and trailing edge caps and erosion strip are also positioned at this time. The entire assembly is then placed in the assembly tool. The internal cavity is pressurized and the structure is cured. After the cure cycle, the flash is removed and the root end is filament wound.

The advantages of the precured leading and trailing half concept are also applicable to this method. Additional ones are: 1) this process produces the lightest composite structure; 2) no dressing of the split lines is required; 3) the secondary bonding of the erosion cap is eliminated; and 4) solid tip sections cause no significant problems.

The disadvantages are that this process requires a two step curing procedure and split lines on the precured spar halves may require special trimming.

This concept appears to be the most promising since it seems to have more advantages and fewer disadvantages than the other two concepts.

Three different root end concepts were studied. A description of each concept is contained below along with a summary of the advantages and disadvantages of each.

The first concept shown in Figure 27 represents a standard coke bottle retention concept. The blade root end fibers wrap around a spherical inner metal mandrel. After sufficient necking, this mandrel reverses and increases in diameter. The reduced cross-section is then filament wound with S-Glass and epoxy resin. Once cured the winding is machined to a taper. An aluminum outer sleeve is bonded over the filament winding. The inner mandrel is positioned relative to the outer sleeve with a thru bolt. Once the bond is cured, the bolt is preloaded to the average centrifugal force value.

The advantages of the coke bottle concept are: 1) the retention is a proven design for composite blades; 2) a metal interface between the blade and hub facilitates sealing the lubricant in the pitch bearing; and 3) the metallic interface also allows attachment of counterweights, snap ring, and external propeller balance weights.

The disadvantages of this retention are: 1) the machining costs are relatively high; 2) it is relatively heavy with two metal parts and the bolt hardware; and 3) individual internal blade balancing is difficult.

The second concept shown in Figure 28 utilizes an internal mandrel similar to the coke bottle, but all the blade loads are transmitted to the mandrel. This eliminates the need for the metal sleeve. The filament winding, due to its small cross section, requires a large material modulus suggesting graphite fibers. The preload on the mandrel is provided by the fiber tension during the filament winding operation.

The advantages of this retention are: 1) the fiber orientation is used in an optimum manner compared to the other concepts; 2) the weight is reduced compared to the coke bottle retention; 3) there is only one metal part that needs machining; and 4) individual internal blade balancing is easier.

The disadvantages are that the fibers and resin are exposed to the pitch bearing lubricant; the external propeller balance weight holes require threaded inserts; the snap ring is bearing in the composite material; and a more expensive counterweight is required if the weight is clamped, or longer bolts are required if the weight is bolted to the inner mandrel.

The third configuration utilizes all composite materials in the construction. As shown in Figure 29, the composite materials transition over a composite mandrel and terminate inboard of the pitch bearing groove. This termination of the fibers causes interlaminar shear stresses and bearing stresses in the composite as the loads are transferred to the split ring of the pitch bearing. The internal mandrel reacts to the hoop loads and is a cavity for the internal blade balance weights. The filament winding performs the same functions as those described for the hybrid concept.

The advantages of this concept are that it is the lightest weight of the three concepts; the potential exists for no machining of metallic parts; and the individual internal blade balancing is easier.

The major disadvantage is that the feasibility of this concept is highly dependent on the hub configuration and geometry. The other disadvantages relate to the filament winding and they are the same as those described for the hybrid concept.

This concept seems to be the most promising of the three presented, but it is doubtful that it could be incorporated into existing hub and retention systems. However, since these areas would probably need to be redesigned for advanced technology propellers, this concept might be applied without undue difficulty.

Structural Considerations

In evaluating the structural integrity of advanced technology propellers considerable attention must be given to the steady and alternating loadings experienced in service. The steady loads consist primarily of centrifugal and thrust forces. The alternating vibratory loads are due to blade aerodynamic excitations, torsional excitations from the reciprocating engine, and resonances with harmonics of rotor speed. Aerodynamic inflow angles mainly excite 1xP alternating loads which generally dominate on conventional turboprop installations, whereas engine alternating torsional loads dominate on conventional reciprocating installations. In all installations one should assure that 1xP resonance does not occur in the normal operating RPM range. The steady loads on conventional propellers can usually be obtained using beam analysis or lumped parameter matrix manipulation techniques. Vibratory analysis is provided by currently available analytical techniques that are applicable to General Aviation propellers. These techniques determine mode frequencies with fair accuracy and vibratory loads and resultant stresses within 25-30 percent on turbine installations. The determination of steady and vibratory effects on advanced technology propellers, incorporating composite materials and having low aspect ratio, sweep and proplets, may require the use of more sophisticated analytical techniques like finite element methods (ref. 13). The effect of alternating excitations from reciprocating engines is currently not included in existing analytical models. Experimental testing of strain gaged propellers is relied upon heavily for both turboprop and reciprocating installations. In addition to assuring propeller blade structural integrity through attention to steady and vibratory load limits, engine firing sequence, and 1xP excitations, a successful design must avoid stall and classical flutter.

Stall Flutter. - Stall flutter is a limit cycle oscillation that occurs at the blade's first natural torsional frequency when the integrated spanwise damping becomes zero or negative. This occurs when the blade is operating at conditions of velocity and angle of attack where significant blade stall is encountered. For propellers, the most critical conditions are the static thrust take-off condition and the reverse thrust landing condition. Stall flutter associated with the reverse pitch braking process can generally be handled by properly adjusting propeller stops to avoid stall. This leaves the static take-off condition as the critical condition from a design standpoint.

The most important point to make relative to the criteria is that the stall flutter characteristic is a function of blade torsional natural frequency, not torsional stiffness. Stall flutter will occur only within certain ranges of reduced velocities where high angles of attack occur and this range diminishes as the mean angle of attack is decreased. Thus to be completely stall flutter free, the designer has a choice of limiting the mean blade angle of attack or increasing the blade natural frequency to such a value that the existence of stall flutter is completely averted at all blade angles. These foregoing extremes in design criteria are generally too restrictive. An optimum design usually determines the best compromise between maximum blade angle expected and the torsional frequency criteria, i.e. for each aerodynamically sized propeller there is a maximum power loading associated with a minimum torsional frequency.

Although inherent structural damping such as available in certain advanced composites can significantly improve stall flutter characteristics, no proven analytical methods are currently available to predict the occurrence of stall flutter and to avoid stall flutter instabilities. However, work is currently underway to extend helicopter aeroelastic prediction techniques to General Aviation.

Empirical reduced frequency parameters are available for use by the G.A. manufacturers on conventional propellers. Unless analytical methods are developed for advanced propellers, the empirical methods will have to be extended by experimental testing.

Classical Flutter. - Classical flutter is an oscillatory instability that can occur at high aircraft velocities by an improper phasing of blade elastic response and aerodynamic loading. Two or more modes of vibration may couple to produce a detrimental phasing of the propeller blade loading. These modes are a function of the design of the propeller blades and are related to the locations of the elastic axis, center of pressure and center of mass, and the blade moments of inertia. The occurrence of classical flutter is related to the spacing of the frequencies of the modes over the propeller operating range.

Existing techniques for predicting mode frequencies are adequate for current technology propellers. These techniques consist of generating a Campbell plot by means of a simple beam theory having a centrifugal stiffening term, and correlating these theoretical results with experimental mode frequency data. The Campbell plot provides a qualitative analysis that determines if the modes are well spaced at operating rpm's. The plot can show if the third or torsion mode is high and unlikely to couple with the first two bending modes. This coupling is the expected situation for classical flutter. The use of the simple beam theory will not be adequate for advanced technology propellers because of their unique shapes (i.e. sweep and proplets), their composite construction, and the fact that the theory does not account for the blade aerodynamic response. Improved analytical techniques, like finite element methods that evaluate blade aerodynamics, will be needed to accurately predict the mode frequencies of the advanced technology propellers. Also, the work currently underway to extend helicopter aeroelastic prediction techniques to General Aviation propellers can be applied to classical as well as stall flutter.

Avoiding Resonances.- Avoiding resonances of integer harmonics (mode coupling) could be a very feasible design task when the blades are to be fabricated with composites. However, the effects of frequency changes with blade pitch must be considered together with the variations in rpm's selected for design. Should this represent a rather wide variation, it may be necessary to sustain a transient through an integer harmonic as the rpm is varied from take-off to a cruise condition. In addition, the systems mounting natural frequency must be considered to avoid whirl flutter type of propeller inducing loads.

The major point is, however, that with the ability to tailor stiffness and mass distributions through the use of composites, the task of controlling the natural frequency and mode shapes should be easy relative to the same task using traditional metal materials. A second major point is that no particular flatwise or chordwise frequency is better than any other as long as resonance is avoided and the amplification of normal propeller loads is within structural integrity limits.

Fatigue. - Because of the high frequency of propeller loadings in the normal aircraft environment, the propeller must be designed for a fatigue endurance limit well above these loads. Generally for turboprop aircraft, the Aq design parameter is selected such that the highly probable gust environment and normal maneuvering environment are contained within this Aq envelope (A is angle of attack and q is dynamic pressure, and this parameter is the measure of the 1 per rev blade loadings).

For piston powered aircraft, the Aq loads are generally overshadowed by the torsional loads induced by the engine through the propeller shaft and/or the motions induced in the propeller plane by the natural frequency of the mounting system.

With a direct material substitution of composites for aluminum, the fatigue strength improves by at least a factor of 2. For example, a material substitution of E-Glass for aluminum in a propeller that has a satisfactory fatigue life will result in excess fatigue strength assuming the blade frequencies still avoid resonances.

Since the resulting design is not critical from a strength standpoint (within the frequency constraints), the potential for reducing the cross-section or thickness of the airfoil and hence the weight is very large.

Experience and fatigue test data on material properties will dictate allowable alternating stress levels and determine the appropriate fatigue limits with composites as is the case with aluminum alloys.

Structural Advantages of Composites. - The advantage of composite materials in propeller blades is that the engineer can readily tailor sections to obtain more favorable stiffness distributions that will control the frequency characteristics and, to a lesser degree, the primary mode shape. Orientation of fibers such as unidirectional or crossply and/or mixed modulus materials are the techniques that are used to optimize strength and frequency characteristics at minimum weight.

Using the loads, frequency, and flutter criteria, as previously discussed, an advanced design would be iterated to obtain a solution that satisfies the strength and frequency criteria and that utilizes the most cost effective combination of materials.

Trade-Offs

This is a complex area to address since the relative importance of each advanced technology area is dependent upon several factors, many of which are subjective in nature and particular to the needs and desires of individual corporate policy. The trade-off analysis of the major propeller design parameters performed by McCauley and the "optimum propeller" design selected for each aircraft are based upon these factors. Therefore, the "optimum propeller" for each aircraft consists of the combination of propeller size, design parameters and advanced technologies which in the opinion of McCauley represent the most suitable propeller for each General Aviation application.

Propeller Optimization

The characteristics of the so-called "optimum" advanced technology propellers designed for each aircraft are shown in Table 5. The optimized propellers shown meet FAR Part 36 and Part 36 - 5dB(A) as indicated. The geometric advanced technology propeller designs are the same for meeting FAR Part 36 and FAR Part 36 - 5dB(A). The advanced technology propellers were originally designed to meet FAR Part 36-5dB(A). The 5dB(A) increase to FAR Part 36 was accomplished by increases in engine rpm rating. At a tip speed above 700 fps, studies have shown that approximately a 100 fps change in the tip speed will affect the overall sound pressure level by about 5dB(A). A basic assumption made here is that engines of the near future can be rated at lower rpm's so that power loading reductions can be controlled by reducing rpm while increasing diameter.

The propellers were optimized first for performance, checked for noise level and iterated back through performance until the required noise level was satisfied and the best performance possible was obtained. The required blade geometry to satisfy performance and acoustics was then checked for structural soundness using appropriate composite materials.

In determining the impact of weight reductions through the use of composites it must be emphasized that the blade weight savings for controllable propellers were a result of a direct replacement of aluminum blades only. This does not take into account any potential weight reductions in the hub area. For fixed pitch propellers a total replacement was assumed. Also, in order to achieve the desired compromise of advanced technologies between performance and noise, the potential weight savings were not necessarily optimum. In other words, the trends of decreased power loading through diameter increases, increased number of blades, sweep and proplets tended to increase weight while being offset partially through lower blade activity factors and lower thickness ratios. Propeller cost (1979 dollars) and weight are determined from the empirical relationships presented in Appendices A and B. Appendices A and B were derived from data presented in reference 14 and modified as required. The characteristics of the optimized advanced technology propellers (Table 5) differ considerably from those of current technology propellers (Table 2) in that they incorporate sweep, proplets, advanced airfoils, have thinner and longer blades, and generally have a larger number of lower activity factor blades. The 11 to 26 percent weight reduction shown by these tables for the advanced technology propellers over the current technology propellers is due to the use of composite materials. Because of their lower weight and higher efficiency the advanced technology propellers required less engine power than the current technology propellers. It is also apparent from a comparison of Tables 2 and 5 that the cost of the advanced technology propellers was higher. The significance of these higher costs will be explained later when addressing Mission Studies.

The potential cruise performance gains obtained by the "optimum" propeller designed for each of the study aircraft are presented in Figure 30. The advanced technology elements affecting performance have been broken down into three categories. Those considered as induced effects include power loading, number of blades, tip speed, and proplets. Blade drag effects include activity factor, thickness ratio, sweep, airfoils and surface finish. Interference effects are attributed to nacelle blockage and spinner/blade shank losses.

The gains in cruise performance from Figure 30 range from about 5 to 9 percent. The higher efficiency gains occurred for the higher speed aircraft, i.e. 414A, 441 and 19 PAX commuter. The higher gains are attributed to greater reductions in interference losses for these aircraft. The gains from interference reduction were 1.3 to 2.3 percent for the lower speed aircraft (172N, A188B, 210M) and 4.2 to 5.0 percent for the higher speed aircraft. Efficiency gains from reductions in induced losses and blade drag losses were fairly constant for all aircraft.

In order to see why efficiency gains attributable to the reduction in interference losses became higher for the higher speed aircraft, Figure 31 was constructed to show the individual contribution of each interference element. From Figure 31 it is evident that the efficiency gains due to improved nacelle blockage effects drops dramatically for two of the higher speed aircraft (441, 19 PAX). This is because of the low nacelle body to propeller diameter ratio of the turboprop installations. It is also clear from this figure that the higher efficiency gains for the higher speed aircraft (414A, 441, 19PAX commuter) are a result of a larger reduction in spinner/blade shank drag. These results are consistent with the fact that the spinner/blade shank drag is a function of dynamic pressure. Thus the amount of drag subject to reduction is larger for the higher speed aircraft.

Aircraft Mission Studies

The propeller trade-offs and resultant "optimum" propeller designs are the driving force affecting important aircraft/mission characteristics. The performance gains shown in Figure 30 and the weight reductions possible through the use of composites that were shown in Table 5 will have a beneficial effect on aircraft/mission characteristics. To determine these effects, a mission study was performed for each aircraft except the A188B. The characteristics of the aircraft with baseline propellers are listed in Table 6. The mission study results for the A188B aircraft were determined by assumed similarities to the 210M aircraft. In performing the mission study, each aircraft was resized to take full advantage of the advanced technology benefits assigned to each "optimum" propeller. Payload, range, speed and aircraft lift to drag ratio were kept constant and a two hour cruise mission was assumed.

Intermediate results of the mission study are presented in Figure 32. These data are the results from a mission analysis computer program and show, for each aircraft, the effects of changes in propeller efficiency and weight on the engine horsepower requirements and aircraft gross weight. The aircraft gross weight reductions resulting from the benefits of the optimized advanced technology propellers were obtained from these data using the efficiency improvements (Figure 30) and weight reductions (Tables 5 and 2) achieved by each advanced technology propeller design. The required power of the advanced technology propeller for each aircraft was determined in a similar manner. The fuel burned was then determined from the power and the specific fuel consumption (Table 6) as:

$$hp \times \% \text{ power} \times SFC \times 2$$

and compared to the fuel burned for the baseline case.

The operating cost of each aircraft was based on a fuel cost of $2 per gallon. The operating cost data for each aircraft were derived from a cost assessment of engine and airframe periodic maintenance, fuel and oil burned, reserves for engine and airframe periodic overhaul, reserves for avionics, systems and miscellaneous items. The resulting relationship between the fuel cost and the operating cost per hour for each baseline propeller-aircraft combination are as follows:

Aircraft	172N	210M	414A	441	19 PAX
Fuel	$18.17	$32.88	$ 74.00	$142.00	$272.34
Operating Cost	$28.73	$53.31	$125.28	$245.25	$427.00

The operating costs of the advanced technology propeller powered aircraft were determined from the above data by assuming that the fuel cost portion of the operating cost was reduced by the same ratio as the fuel savings but that the remaining portion of the operating cost was constant.

The aircraft retail cost reduction resulting from the application of advanced technology propellers was determined from the weight savings of the resized aircraft combined with the price per pound determined from Table 6, and included the increased cost of the advanced technology propeller.

The results of the mission studies showing the benefits of the advanced technologies that were applied to obtain an "optimum" propeller for each aircraft are presented in Figures 33 through 36. These figures show the percentage gains of the advanced technology propeller powered aircraft over the baseline propeller powered aircraft. The gains are shown for the advanced technology propeller powered aircraft that meet the FAR Part 36 noise constraint and the FAR Part 36 - 5dB(A) noise constraint. Both cases are compared to baseline propeller powered aircraft that meet only the FAR Part 36 noise level. The difference in the advanced technology propeller gains between these noise levels represents a potential penalty associated with the more stringent noise regulation.

The data presented in Figure 33 for the FAR Part 36 noise constraint show that the application of advanced technology to General Aviation aircraft has the potential of reducing aircraft trip fuel consumption by 8 to 18 percent. The results of this study also indicate that the fuel savings would vary with the type of aircraft, with the smaller, lower cruise speed aircraft having a fuel savings of 8 to 10 percent and the larger, higher cruise speed aircraft having a fuel savings of 14 to 18 percent. The effects of a more severe future noise constraint on the advanced technology propeller powered aircraft was also studied and indicated that fuel savings would be reduced by about one percent should a 5dB(A) lower noise level be required.

With advanced technology propellers, aircraft operating costs were reduced about 5 to 6 percent (Fig. 34, FAR 36) and showed no significant variation with the type of aircraft studied. The aircraft retail acquisition costs were reduced about 8 to 16 percent with the application of advanced technology propellers (Fig. 35, FAR 36). Although the cost savings varied considerably, there was no large aircraft related trend to the data. Both the operating and acquisition cost savings would be diminished by about 1 percent or less if the 5dB(A) lower noise level were imposed. The operating cost gains were due primarily to the fuel savings and the retail cost gains to the reduction in the size and associated cost for the airframe/engine of the resized aircraft. The higher advanced technology propeller costs (comparing Tables 2 and 5) did not significantly influence the retail aircraft costs as retail propeller costs represented less than 4 1/2 percent of these costs for the aircraft considered in this study.

Aircraft weight when resized to benefit from the application of advanced propeller technology, was reduced about 6-10 percent for the FAR Part 36 noise level case (Fig. 36). This improvement was reduced by less than 1 percent when the 5dB(A) lower noise limit was applied to the advanced technology propeller/aircraft.

Technology Program Plan

It is apparent from this study that advancements in propeller technology can provide significant performance and cost improvements in future General Aviation aircraft. A technology program with attention to advanced analytical prediction methods, composite materials and other promising concepts, is needed to develop the technology and integrate it into a design system suitable for use by the General Aviation industry. The general technology elements of this program are shown in Figure 37. This program would develop the technology for more efficient, quieter, safer and lighter weight propellers; integrate these technologies into a design system suitable for use by the G.A. industry; and verify this technology in a model and full scale program.

The technology development activities would include a detailed evaluation to determine the design technologies and new or improved analyses that would be required to adequately design future advanced G.A. propellers. This evaluation would define the improvements needed in each technology area (i.e., aerodynamics, composites, aeroelastics, and acoustics) to achieve a workable, unified design methodology. Attractive advanced technology concepts (such as proplets, sweep, aero-acoustic airfoils, hybridized composites, and advanced composite blade design concepts) would be identified in the evaluation and a preliminary assessment of these would determine the potential benefit of each. Concepts showing the highest potential would be selected for further analytical and experimental evaluation.

Upon completion of this detailed evaluation study, advanced technologies would be developed in the areas of aerodynamics, acoustics, aeroelastics, and composite structures.

In the area of aerodynamics and more specifically advanced airfoil design, NASA has continually made efforts in improving communications with the General Aviation community over the past several years through workshops, symposiums, conferences, etc., and from these have come airfoil design implementation schedules satisfying the needs of wing designers. What is needed now is an airfoil technology plan to design airfoils specifically tailored for the widely varying fluid flow conditions which prevail along a propeller blade.

Advanced airfoils not only have the potential to improve propeller efficiency, but also (and perhaps more importantly) to lower the activity factors required for peak performance at a given design condition and thereby reduce propeller weight.

Three dimensional flow field analytical techniques that account for the presence of the propeller and nacelle must be developed to the point of commercial acceptability. There should be future testing including a wide variety of propeller/nacelle configurations covering the broad range of aircraft/engine combinations typical of the General Aviation fleet.

Flow field analysis must be expanded to include the previously mentioned interference effects between the spinner and blade shank that were reported from the results of recent wind tunnel testing at NASA-Lewis Research Center. Additional effort is needed to better quantify and understand the mechanism behind this interference phenomenon. NASA should support analytical studies to predict spinner-shank interference effects which could then be incorporated into strip analysis techniques for a more accurate determination of installed propeller performance.

Aerodynamic design technology should include analyses that properly account for advanced concepts such as sweep and proplets, for example, and assess propeller/nacelle/aircraft interactions in addition to propeller/spinner interference effects.

In order to adequately assess the structural feasibility of various composites for advanced propellers, new high technology analysis is required. In addition, design and manufacturing concepts must be developed. Manufacturing concepts including tooling requirements and process development must be studied in detail for specific applications, weighing the advantages of each. The result would be a preliminary design that incorporates the root attachment, amount of core, fiber-matrix system, leading edge and tip treatments, etc. The preliminary design would then be analyzed by three dimensional finite element analysis since several assumptions are inherent in the initial design. Modeling allows economical iterations in the convergence process to a final design.

The total cost of composite blades must be nearly competitive with aluminum blades in order to experience wide use in General Aviation. Research into low cost fabrication techniques and proper design procedures are the key to achieving cost competitiveness.

It appears that composites will first see wide spread commercial applications on large, complex, highly sophisticated multi-engine type aircraft where each pound of propeller weight savings has a significant impact.

On the other hand, it is important that composites are studied for high volume reciprocating engine applications where quantity will dictate feasibility rather than a large effect on a per aircraft basis.

Recommended technology in aeroelastics would include development of better unsteady aerodynamics and structural dynamic analyses to better model propeller forced excitations and evaluate flutter characteristics.

Since many technology elements that improve performance have an adverse effect on acoustics, and future government regulations controlling noise limits will probably be more stringent, it is strongly recommended that research funding be expended in this area. The acoustic technology improvements should include the development of analytical programs to accurately predict the noise of propellers incorporating advanced concepts and to evaluate attractive noise reduction approaches. Also, structure borne noise must be evaluated as it may be a significant contribution to cabin noise.

A five year research program is recommended to implement the development of the above propeller technologies and integrate them into a useable design system. The proposed program is structured to advance the various propeller technologies to the point of acceptable readiness for commercial development by the end of the five year effort. The details and time schedules of the research that is proposed in each technology area are presented in Table 7.

SUMMARY OF RESULTS

Advanced propeller technologies with the potential for improving aircraft characteristics such as fuel burned, operating cost, acquisition cost, and gross weight were studied. Technology elements that could increase propeller performance and reduce source noise were identified and evaluated. Composite materials suitable for propeller blades were selected and their design and manufacturing techniques were investigated. Also, methods of assuring propeller blade structural integrity were addressed. The information thus generated was combined to define an "optimum" advanced technology propeller for each of the aircraft included in the study. A mission analysis was then performed to quantify the advantages of the "optimum" propeller powered aircraft over baseline propeller powered aircraft.

Propeller technology elements that could increase performance (i.e. efficiency) were identified and divided into two categories; normal propeller design variables and advanced concepts. Increases in propeller efficiency were provided by the following changes in design variables: decreased power loading, blade thickness ratio and activity factor; and increased tip speed and number of blades. The advanced concepts that provided increased efficiency were NASA proplets, blade sweep, advanced airfoils and improved surface finish resulting from the use of advanced composite materials. A reduction of interference effects from improved propeller/nacelle integration and better spinner/blade shank blending also increase propeller performance.

The technology elements with the potential to decrease noise while increasing performance included increasing the number of blades, incorporating sweep and reducing thickness within structural limits. Reducing tip speed and moving peak blade loading inboard reduced noise but also performance. Activity factor reductions lowered noise but could reduce performance in cases where higher activity factors are needed. NASA proplets and advanced airfoils have some small potential for reducing noise.

Future propeller blades constructed from composite materials promise propellers of lighter weight and better performance with lower noise and greater safety margins. Therefore, appropriate composite materials were screened and four were selected and evaluated: E-Glass, S-Glass, Kevlar, and Graphite. E-Glass and Kevlar appear to be the best choice of materials for the near term. The high cost of Graphite would preclude its use except when its high strength characteristics were required.

A study was made of the various composite manufacturing techniques that were applicable to propeller blade construction. Due to the compound curvature of advanced propeller blade configurations, the best leading edge protection was afforded by an erosion cap of electroformed nickel. Manufacturing processes using tape goods in the form of prepreg materials were chosen as optimum. Three blade mold processes and three root end concepts were investigated. Results are presented and discussed.

The structural integrity of advanced technology propeller blades depends on a proper structural design that considers steady loads, vibratory fatigue limits, engine firing sequence, stall flutter, classical flutter, and resonance avoidance. A discussion of these factors is presented. With composite materials, tailoring of the composite matrix will allow control of thickness, mass, and stiffness distribution to a degree not possible with metal blades. The dynamic and strength characteristics can be optimized to allow the construction of advanced blades that are thinner, have sweep and NASA proplets, and a lower activity factor than heretofore possible. However, to achieve these ends, improved aeroelastic technology is necessary to better evaluate unsteady aerodynamics, structural dynamics, model propeller forced excit tions and evaluate flutter characteristics.

The advanced technology propellers defined in this study have composite material blades and incorporate sweep, NASA proplets, and advanced airfoils; and generally have a larger number of thin, low activity factor blades. They are 11 to 26 percent lighter than current technology propellers. They provided gains in cruise efficiency of about 5 to 9 percent. The higher gains occurred for the higher speed aircraft due to a reduction of the interference losses which are larger at higher speeds.

Aircraft with advanced technology propellers achieved the following gains over baseline propeller powered aircraft, with both the baseline and advanced technology cases meeting an FAR Part 36 noise constraint:

Aircraft fuel savings ranged from 8 to 10 percent for the lower speed aircraft and 14 to 18 percent for the higher cruise speed aircraft.

Aircraft operating costs were reduced about 5 to 6 percent and aircraft retail acquisition costs were reduced about 8 to 16 percent. These costs showed no significant trend with aircraft type.

Aircraft weight from resizing was reduced about 6 to 10 percent.

When advanced technology propeller powered aircraft were constrained to FAR Part 36-5dB(A) and compared to baseline propeller powered aircraft at FAR Part 36, the above gains were diminished about 1 percent or less.

A five year research program was recommended to implement the development of advanced aerodynamics, composite technology, aeroelastics, and improved noise prediction methodology, and to integrate them into a usable propeller design system.

APPENDIX A

GENERALIZED PROPELLER LIST PRICE PER POUND EQUATION
(1979 Dollars)

(U.S. Customary Units)

$$P = 3.2\ (3B^{.75} + E)$$

Where:

P = Propeller list price per pound

P_C = Adjusted P for propellers utilizing composite materials

B = Number of blades

E = Empirical factor (see table below)

RP = Relative list price factor for various composite materials

F = Miscellaneous expense factor for composites = 1.2

PROPELLER TYPE		E
(1)	All fixed pitch propellers	1.1
(2)	All non-counterweighted, non-feathering, constant speed propellers	1.5
(3)	All non-reverse, counterweighted, full feathering propellers	2.5
(4)	All constant speed, counterweighted, full feathering, reverse propellers	5.8

For propeller type (1) entirely composite, P_C = RPxPxF

For propeller types (2-4) with composite blades,

$$P_C = (.55 + .45\ RP)\ P \times F$$

Where RP is as indicated below:

	RP
E-Glass	1.2
S-Glass	1.3
Kevlar	1.3
Graphite	1.8

NOTE: F includes tooling amortization and engineering expense associated with new technology.

P and P_C are price per pound numbers which must be multiplied by the propeller weight for total propeller list price determination.

APPENDIX B

GENERALIZED PROPELLER WEIGHT EQUATION

(U. S. Customary Units)

$$W_T = K_W \left[\left(\frac{D}{10}\right)^2 \left(\frac{B}{4}\right)^{0.7} \left(\frac{AF}{100}\right)^u \left(\frac{ND}{20,000}\right)^v \left(\frac{SHP}{10D^2}\right)^{0.12} (M+1)^{0.5} \right] + C_W + K_E$$

Where:

W_T = Propeller net weight, lbs. (excludes spinner, deicing & governor)

W_C = Adjusted wt. for propellers using composite materials

R_W = Relative blade weight factor for various composite materials

D = Propeller diameter, ft.

B = Number of blades

AF = Blade activity factor

N = Propeller speed, RPM (take-off)

SHP= Shaft horsepower, HP (take-off)

M = Mach No. (design condition: max. power cruise)

$$C_W = y\left(\frac{D}{10}\right)^2 (B) \left(\frac{AF}{100}\right)^2 \left(\frac{20,000}{ND}\right)^{0.5} = \text{counterweight wt., lbs.}$$

K_E = 1.5 lbs. per inch of propeller extension

K_W, u, v and y Values for use in the weight equation are taken from table below

Propeller types associated with above K_W are as follows:

		K_W	u	v	y
(1)	All fixed pitch props	170	.9	.35	0
(2)	All non-counterweighted, non-feathering, constant speed props	200	.9	.35	0
(3)	All non-reverse, counterweighted, full feathering props	210	.7	.40	3.5
(4)	All constant speed, counterweighted, full feathering, reverse props	180	.7	.40	3.5

Adjustment of W_T for propellers utilizing composite materials
For propeller type (1) entirely composite, $W_C = R_W \times W_T$
For propeller types (2-4) with composite blades, $W_C = (.4 + .6\ R_W)\ W_T$
Where R_W is as indicated below:

	R_W
E-Glass	.73
S-Glass	. 7
Kevlar	. 5
Graphite	.45

APPENDIX C

SYMBOLS

AF	blade activity factor
	$= \frac{100,000}{16} \int_{hub}^{r/R=1.0} b/D(r/R)^3 d(r/R)$
b	local blade chord, cm (in.)
C_p	power coefficient = $P/\rho_o n^3 D^5$
D	blade tip diameter, cm (in.)
dB(A)	A-Weighted Noise Level in Decibels, with a reference of 20uPa (0.0002 dynes/cm^2)
hp	horsepower
J	advance ratio, V_o/nD
n	rotational speed, revolutions per second
P	power, kW (ft-lb/sec)
R	blade tip radius, cm (in.)
r	radius, cm (in.)
SHP	shaft power, kW (hp)
T	thrust, N(lb)
t	local blade thickness, cm (in.)
TAF	total activity factor = blade activity factor X number of blades
V_o	free-stream velocity, m/sec (ft/sec)
Δ	change
η_i	ideal propulsive efficiency = $(T_{ideal} \cdot V_o)/P$ (excludes blade profile drag and compressibility losses)
η	efficiency = $(T \cdot V_o)/P$
ρ_o	free-stream density, kg/m^3 (slugs/ft^3)

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TABLE 1. - BASELINE AIRCRAFT

Aircraft Type	Designation	Cruise Speed m/sec (knots)	Sea Level Static Power kW (hp)
Agricultural	Cessna 188B	54.1 (105)	212.5 (285)
Single Reciprocating Engine	Cessna 172N	61.0 (118.5)	119.3 (160)
Single Reciprocating Engine	Cessna 210M	86.2 (167.5)	212.5 (285)
Twin Reciprocating Engine	Cessna 414A	110.4 (214.5)	231.2 (310)
Twin Turboprop	Cessna 441	150.8 (293)	473.5 (635)
Turboprop Commuter	Cessna 19 PAX STAT (Ref. 1)	148.3 (288)	820.3 (1100)

TABLE 2. - CURRENT TECHNOLOGY PROPELLER CHARACTERISTICS

Aircraft	172N	210M	414A	441	A188B	19 PAX
Engine	Lycoming O-320-H2AD	Continental IO-520-L	Continental TSIO-520-NB	Airesearch TPE331-8-403S	Continental IO-520-D	Pratt & Whitney PT65 Series
Shaft Power, kW (hp)	119.3 (160)	212.5 (285)	231.2 (310)	473.5 (635)	212.5 (285)	947.0 (1270)
RPM	2700	2700	2700	2000	2700	1700
Propeller Model	1C160/DTM	D3A34C404/ 80VA-0	3AF32C93/ 82NC-5.5	3GFR34C601/ 93JA-3	D3A32C90/ 82NC-2	N/A
Diameter, m (in)	1.91 (75)	2.03 (80)	1.94 (76.5)	2.29 (90)	2.03 (80)	2.79 (110)
Number of Blades	2	3	3	3	3	3
Tip Speed, m/sec (ft/sec)	269.7 (885)	287.1 (942)	274.6 (901)	239.3 (785)	287.1 (942)	248.7 (816)
Total Activity Factor	170	243	267	390	240	360
t/b @ 3/4 R.	.085	.081	.083	.065	.080	.063
Airfoil Type	RAF-6	CLARK Y	RAF-6	16-64 Series	RAF-6	16-64 Series
Tip Sweep	0°	0°	0°	1°	0°	.5°
Proplets	None	None	None	None	None	None
*Weight, kg (lbm)	16.2 (35.8)	30.8 (68.0)	31.8 (70.2)	52.9 (116.6)	29.5 (65.0)	75.4 (166.2)
**Cost (1979 $)	$704	$1814	$2098	$4715	$1734	$6721
Material	aluminum	aluminum	aluminum	aluminum	aluminum	aluminum

* Note: Weight includes hub, blades, and controls.

** Note: Cost is retail list.

TABLE 3. - TECHNOLOGY ELEMENTS AFFECTING PERFORMANCE

Technology Element	Performance Loss To Be Minimized	Reference Utilized
	Induced	
Decreased power loading	Axial momentum	2
Tip speed	Tip and swirl	2
Increased number of blades	Tip	2
NASA proplets	Tip	3
	Blade Drag	
Sweep (reduced helical tip Mach number)	Compressibility	4, 5
Advanced technology airfoil	Compressibility, profile drag	15
Decreased thickness ratio	Compressibility, profile drag	4, 5
Improved surface finish	Friction drag	6, 16, 17
Decreased activity factor	Profile drag	4, 5
	Interference	
Improved propeller/nacelle integration	Blade drag, nacelle drag	4, 5, 8
Spinner/blade shank blending	Blade drag, interference drag	6, 9

TABLE 4. - TECHNOLOGY ELEMENTS AFFECTING ACOUSTICS

Technology Element	Reference Utilized
Increased number of blades	18, 19
Decreased tip speed	18, 19
Decreased activity factor	18, 19
Proplets	3, 18, 19
Peak blade loading moved inboard	18, 19, 20
Sweep	12, 18, 19, 20
Advanced technology airfoils	18, 19
Decreased thickness ratio	18, 19

TABLE 5. - ADVANCED TECHNOLOGY PROPELLER CHARACTERISTICS

Aircraft	172N	210M	414A	441	A188B	19 PAX
*Shaft Power, kW (hp)	108.1 (145)	201.3 (270)	193.9 (260)	384.0 (515)	205.1 (275)	801.6 (1075)
*RPM	2665	2653	2699	2051	2653	1818
* ip Speed, m/sec (ft/sec)	294.1 (965)	317.6 (1042)	305.1 (1001)	272.8 (895)	317.6 (1042)	290.2 (952)
**Shaft Power, kW (hp)	109.6 (147)	202.8 (272)	196.1 (263)	391.5 (525)	207.3 (278)	805.4 (1080)
**RPM	2388	2399	2429	1822	2399	1627
**Tip Speed, m/sec (ft/sec)	263.7 (865)	287.1 (942)	274.6 (901)	242.3 (795)	287.1 (942)	259.7 (852)
Diameter, m (in)	2.11 (83)	2.29 (90)	2.16 (85)	2.54 (100)	2.29 (90)	3.05 (120)
Number of Blades	2	4	4	4	4	5
Total Activity Factor	170	243	267	390	240	360
t/b @ 3/4 R.	.060	.060	.063	.040	.060	.040
Airfoil Type	Advanced	Advanced	Advanced	Advanced	Advanced	Advanced
Tip Sweep	25°	25°	25°	25°	25°	25°
***Proplets	5% h/R	5% h/R	5% h/R	5% h/R	5% h/R	5% h/R
****Weight, kg (lbm)	14.4 (31.8)	25.1 (55.3)	27.0 (59.6)	45.0 (99.1)	21.9 (48.2)	57.7 (127.2)
*****Cost (1979 $)	$900	$2406	$2854	$6169	$2045	$8777
Material	E-Glass	Kevlar	Kevlar	Kevlar	Kevlar	Kevlar

* Note: Satisfying FAR Part 36.
** Note: Satisfying FAR Part 36-5dB(A).
*** Note: h/R is proplet height to blade radius ratio.
**** Note: Weight includes hub, blades, and controls.
***** Note: Cost is retail list.

TABLE 6. - CURRENT AIRCRAFT STATISTICS

AIRCRAFT	172N	210M	414A	441	19 PAX
FUEL BURNED, kg (lbm) 2 Hour Cruise	46.7 (103)	83.5 (184)	187.3 (413)	454.1 (1001)	799.7 (1763)
CRUISING ALTITUDE, m (ft)	2438.4 (8000)	1981.2 (6500)	7315.2 (24000)	7315.2 (24000)	4572.0 (15000)
CRUISING POWER Percent of Max Power	75%	75%	77.5%	75%	61%
MAXIMUM CONTINUOUS SHAFT POWER, kW (hp)	119.3 (160)	212.5 (285)	231.2 (310)	473.5 (635)	932.1 (1250)
RPM	2700	2700	2700	2000	1700
CRUISING SPEED, m/sec (knots)	61.0 (118.5)	86.2 (167.5)	110.4 (214.5)	150.8 (293)	148.3 (288)
SFC at CRUISE (per engine) kg/kW-hr (lbm/hp-hr)	.262 (.430)	.262 (.430)	.262 (.430)	.320 (.526)	.353 (.58)
PRICE UNEQUIPPED (1979 $)	$25,950	$67,995	$362,740	$850,000	$1,242,000
EMPTY WT, kg (lbm)	655.0 (1444)	965.7 (2129)	2049.8 (4519)	2535.2 (5589)	3982.6 (8780)
TAKEOFF GROSS WT, kg (lbm)	1043.3 (2300)	1723.7 (3800)	3075.4 (6780)	4468.0 (9850)	7257.6 (16000)

Table 7 - Schedule for Proposed Research Program

ADVANCED CONCEPTS AND TECHNOLOGY EVALUATION

YEAR 1 2 3 4 5

AERODYNAMICS
- AIRFOIL TECHNOLOGY DEVELOPMENT
- PROPELLER / NACELLE INTERACTIVE ANALYSIS
- SPINNER / BLADE SHANK INTERACTIVE ANALYSIS
- IMPROVED AERODYNAMIC PERFORMANCE ANALYSIS
- WIND TUNNEL TESTING
- FULL SCALE DESIGN, FABRICATION AND TESTING

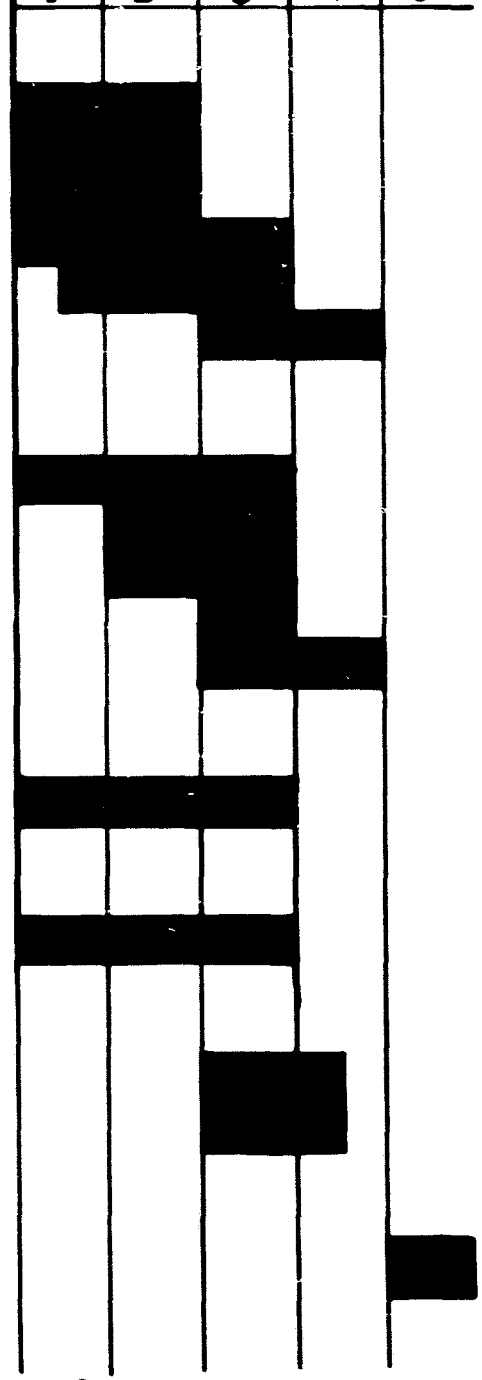
COMPOSITES
- IMPROVED ANALYSIS CAPABILITIES
- DESIGN CONCEPTS
- MANUFACTURING, TOOLING AND PROCESS DEVELOPMENT
- FULL SCALE DESIGN
- FULL SCALE FABRICATION AND FLIGHT TESTING

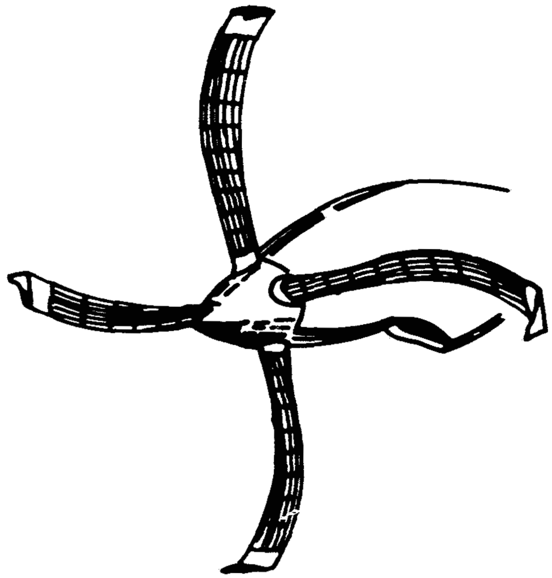
AEROELASTICS
- IMPROVED VIBRATORY STRESS PREDICTION METHODOLOGY

NOISE
- IMPROVED NOISE PREDICTION METHODOLOGY

DESIGN OPTIMIZATION
- AERO / ACOUSTICS
- COMPOSITE STRUCTURES

FLIGHT VERIFICATION
- PERFORMANCE, NOISE AND STRUCTURAL INTEGRITY





IDENTIFY ADVANCED TECHNOLOGIES

ASSESS BENEFITS, COSTS & RISKS

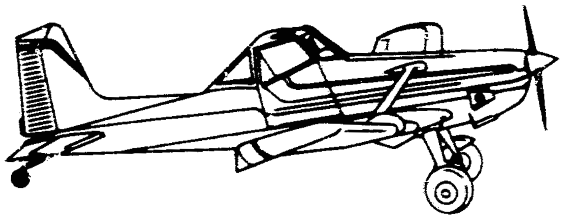
DEFINE OPTIMUM CONFIG., MISSION ANALYSIS

RECOMMEND TECHNOLOGY PROGRAM

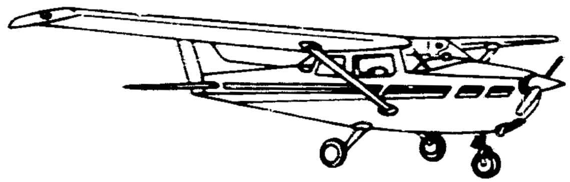
Figure 1.- Advanced technology propeller study.

- McCAULEY
  PROGRAM MANAGEMENT, PERFORMANCE, COST, STRUCTURES
- CESSNA
  AIRPLANE MISSION ANALYSIS
- OHIO STATE
  ACOUSTICS
- MATERIALS SCIENCES & SAI
  COMPOSITES

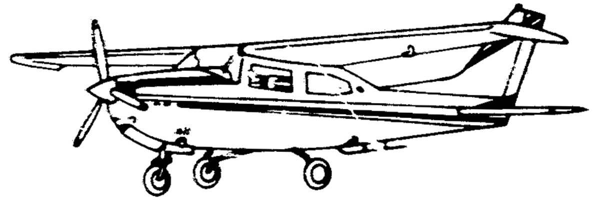
Figure 2.- Team comprising study effort.



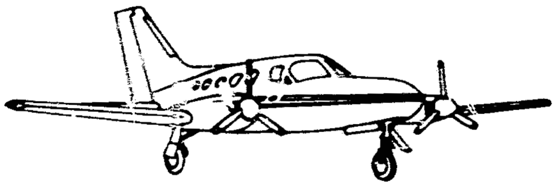
CESSNA A188B



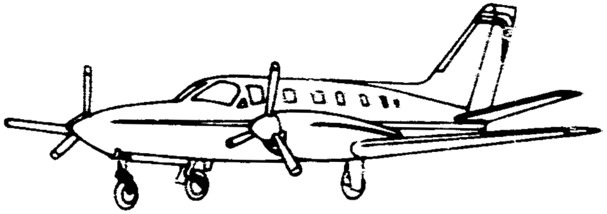
CESSNA 172N



CESSNA 210M



CESSNA 414A



CESSNA 441

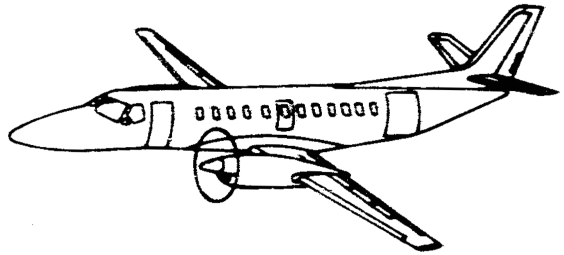


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Figure 3.- Baseline aircraft studied.

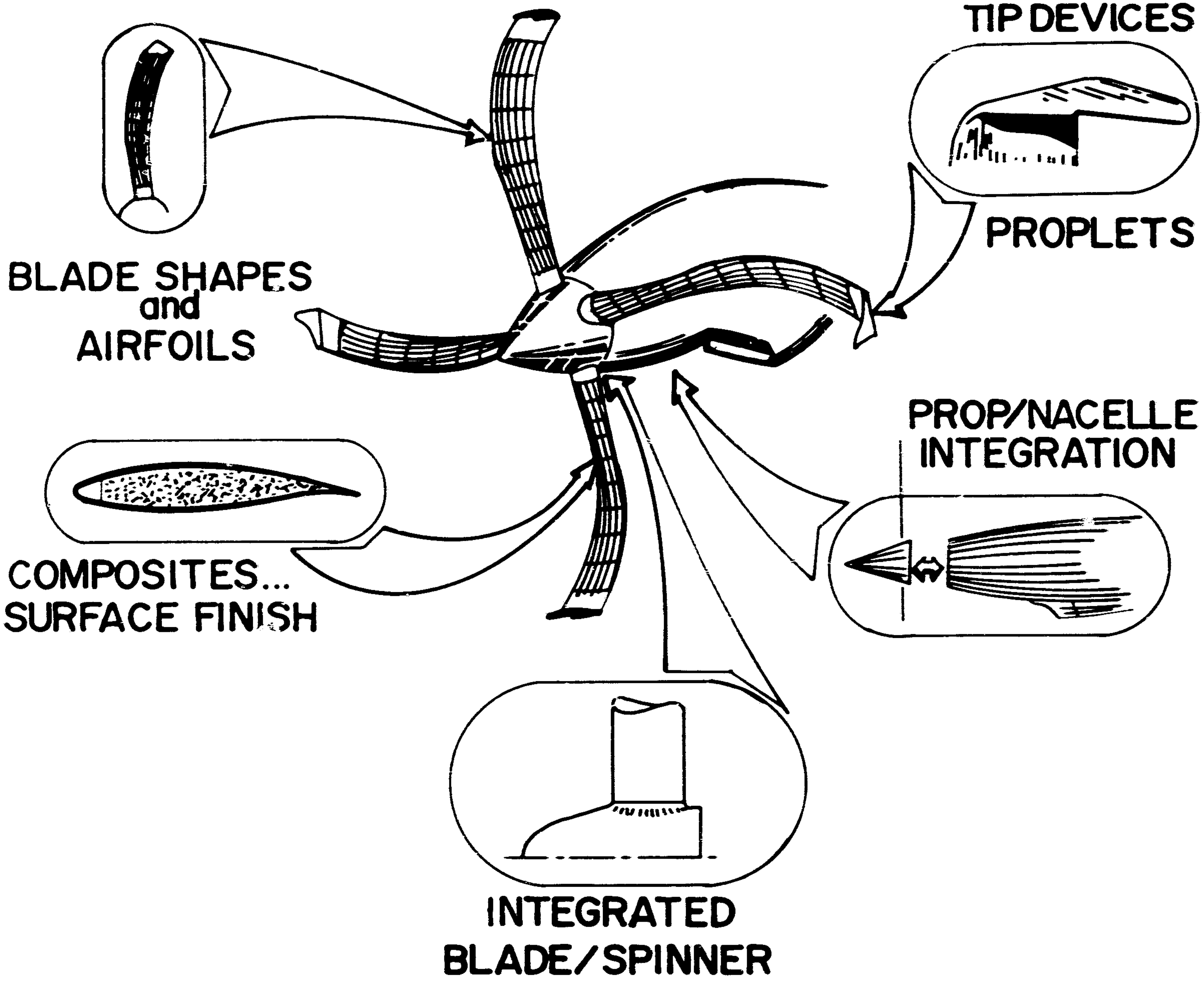
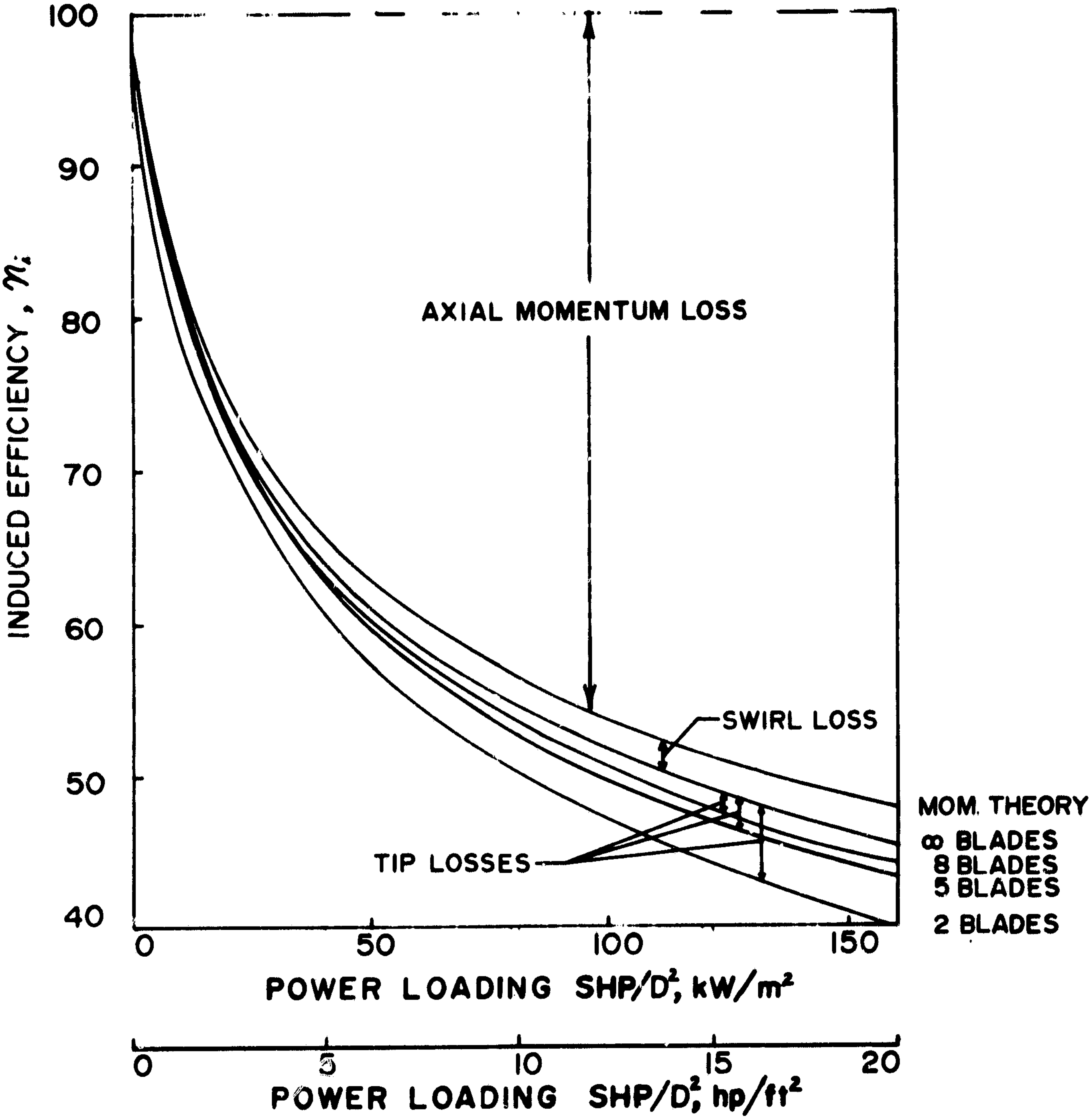
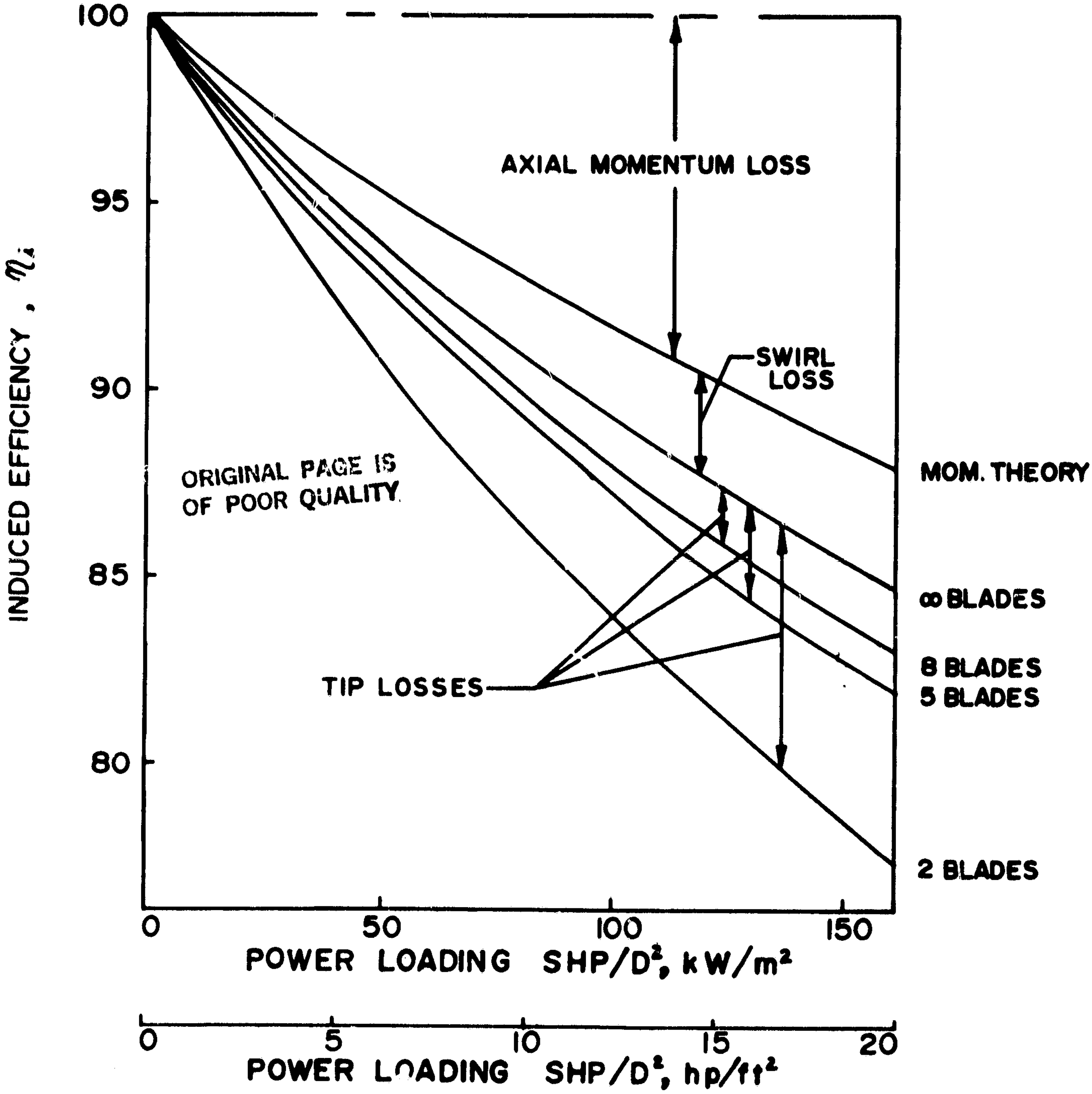


Figure 4. - Advanced technology concepts.



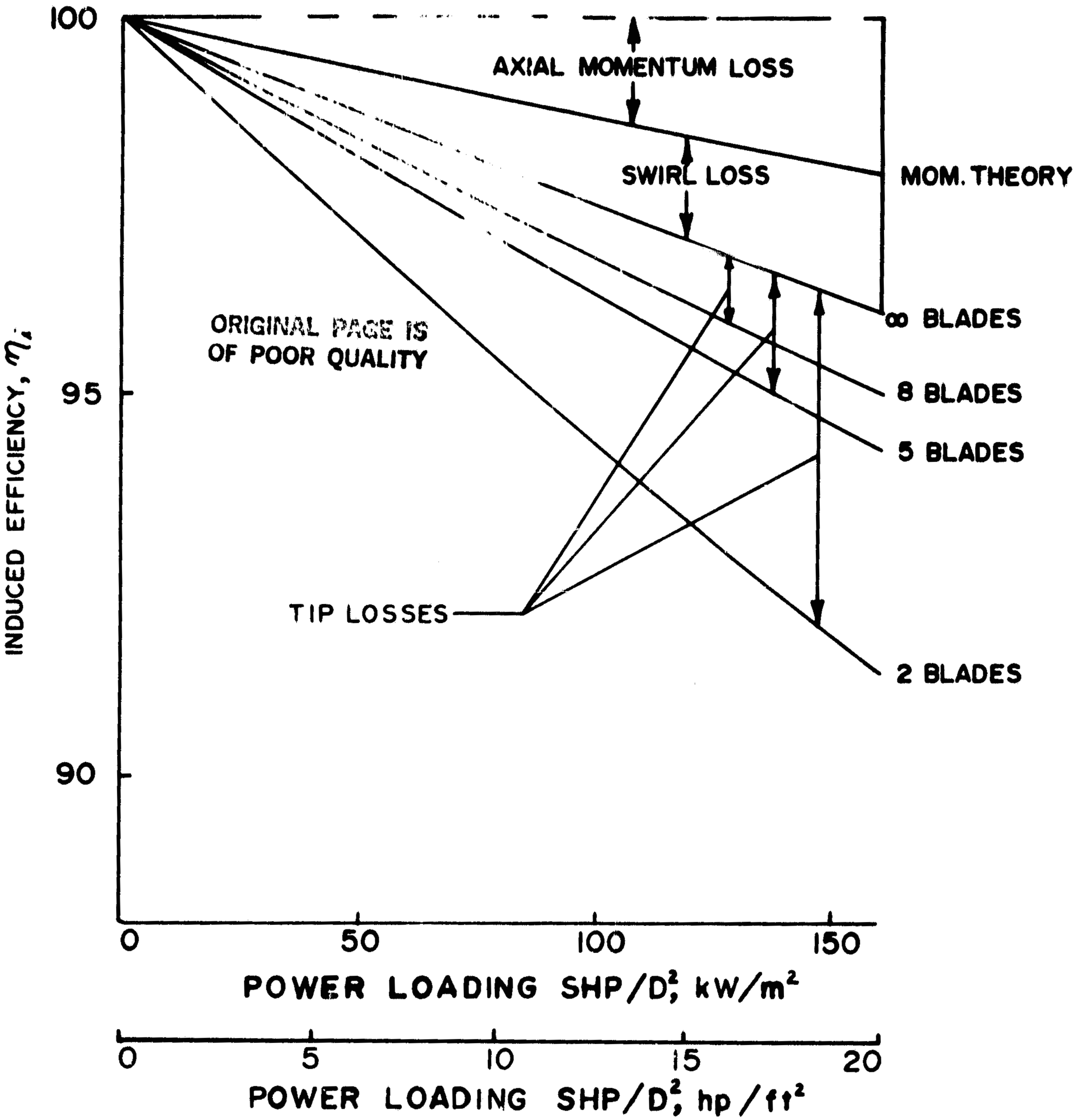
(a) Airspeed, 26 m/sec. (50 knots)

Figure 5.- Effect of power loading and number of blades on induced efficiency: 274 m/sec. (900 ft/sec.) tip speed at sea level standard conditions.



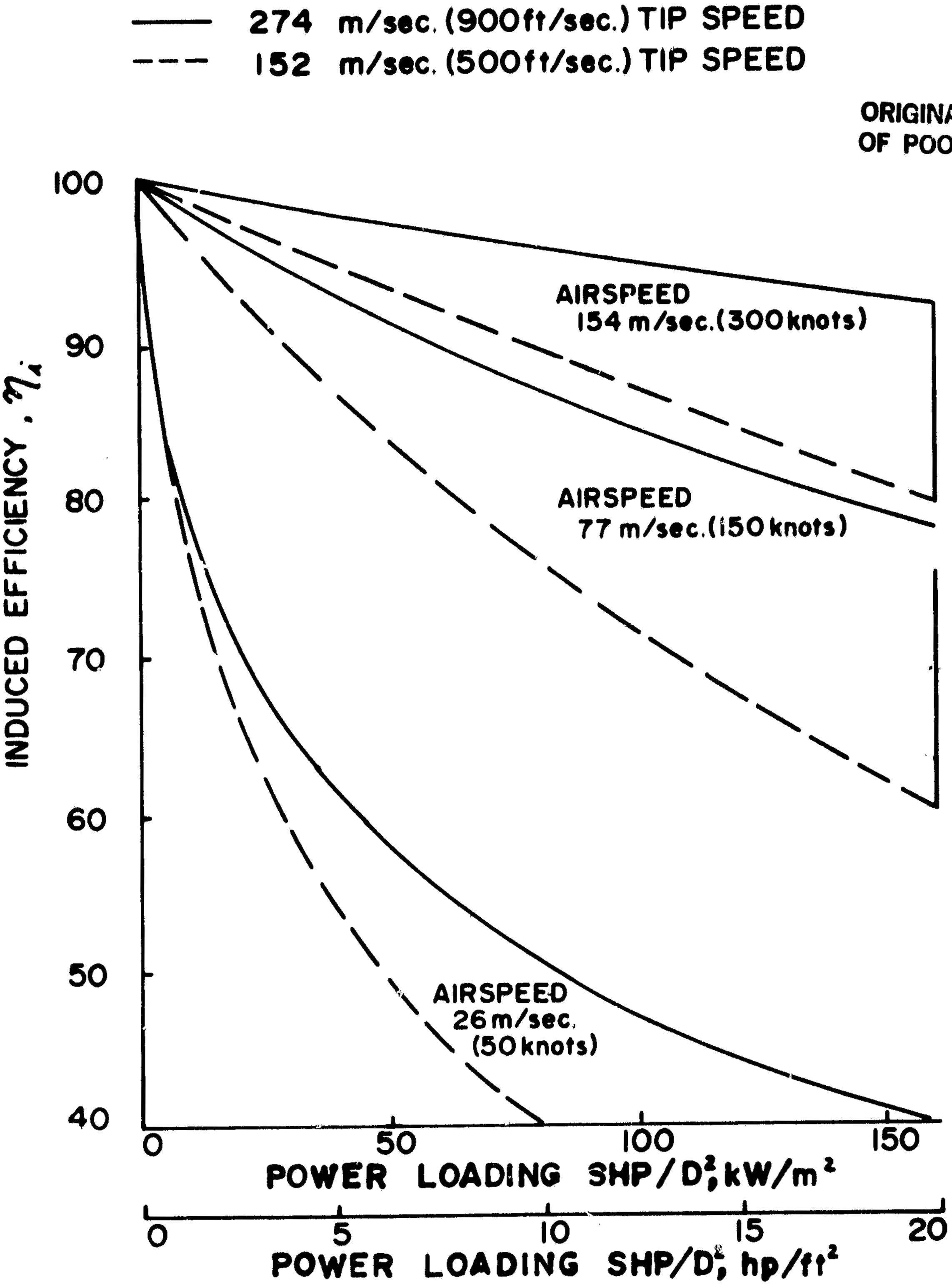
(b) Airspeed, 77 m/sec. (150 knots)

Figure 5. - Continued



(c) Airspeed, 154 m/sec.(300 knots)

Figure 5.- Concluded



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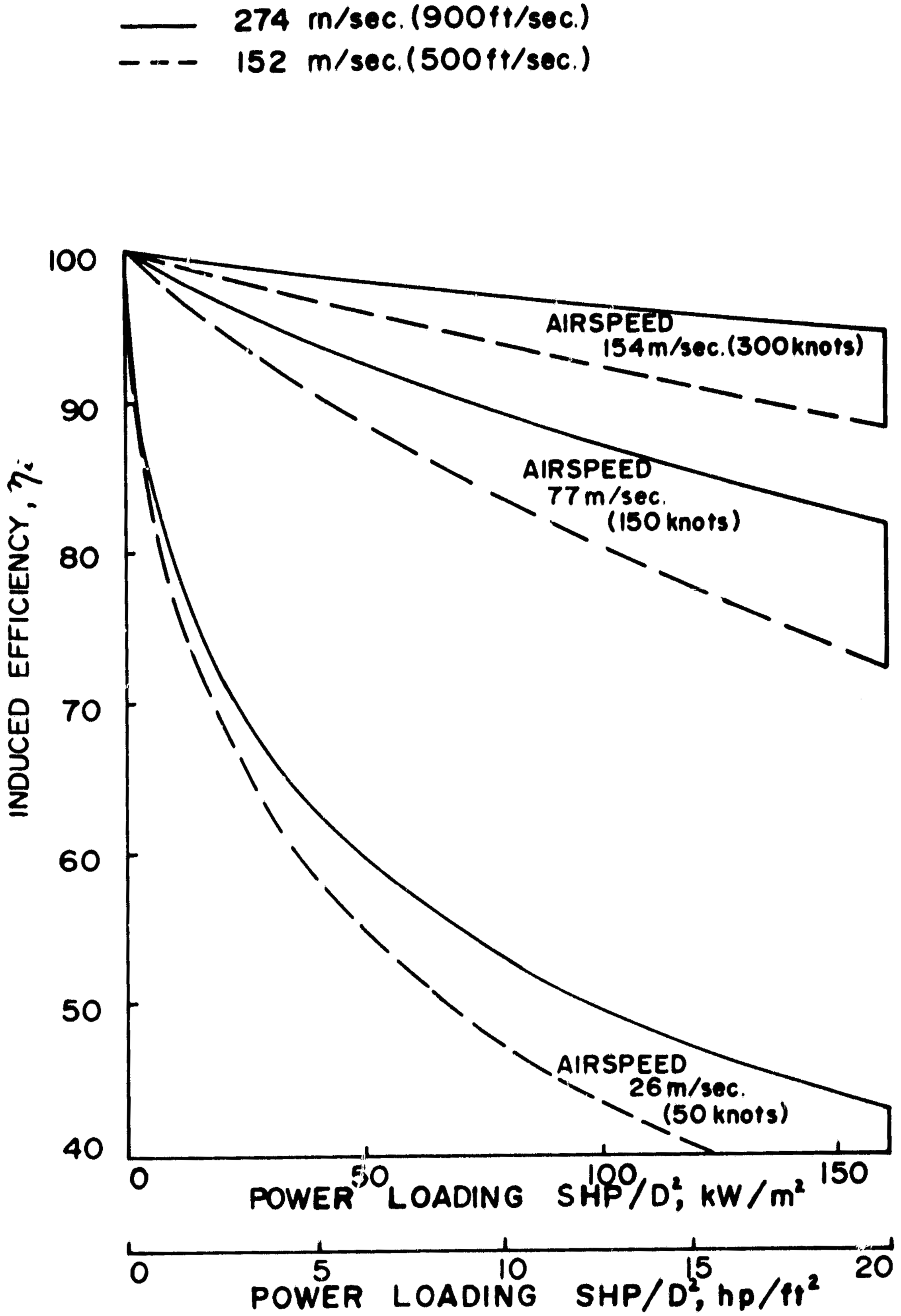
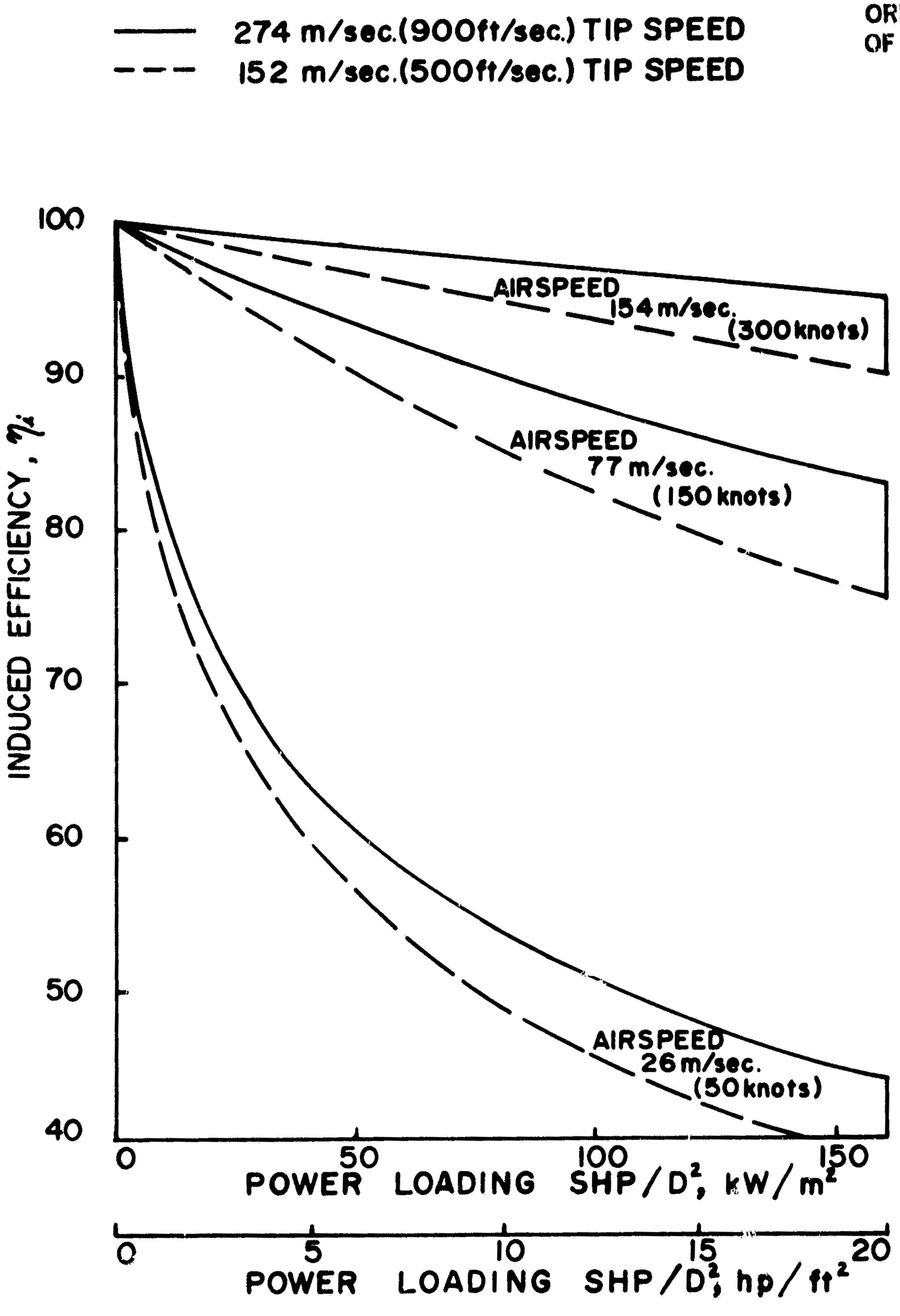
(a) 2 Bladed Propellers

Figure 6.- Effect of power loading, tip speed and airspeed on induced efficiency at sea level standard conditions.



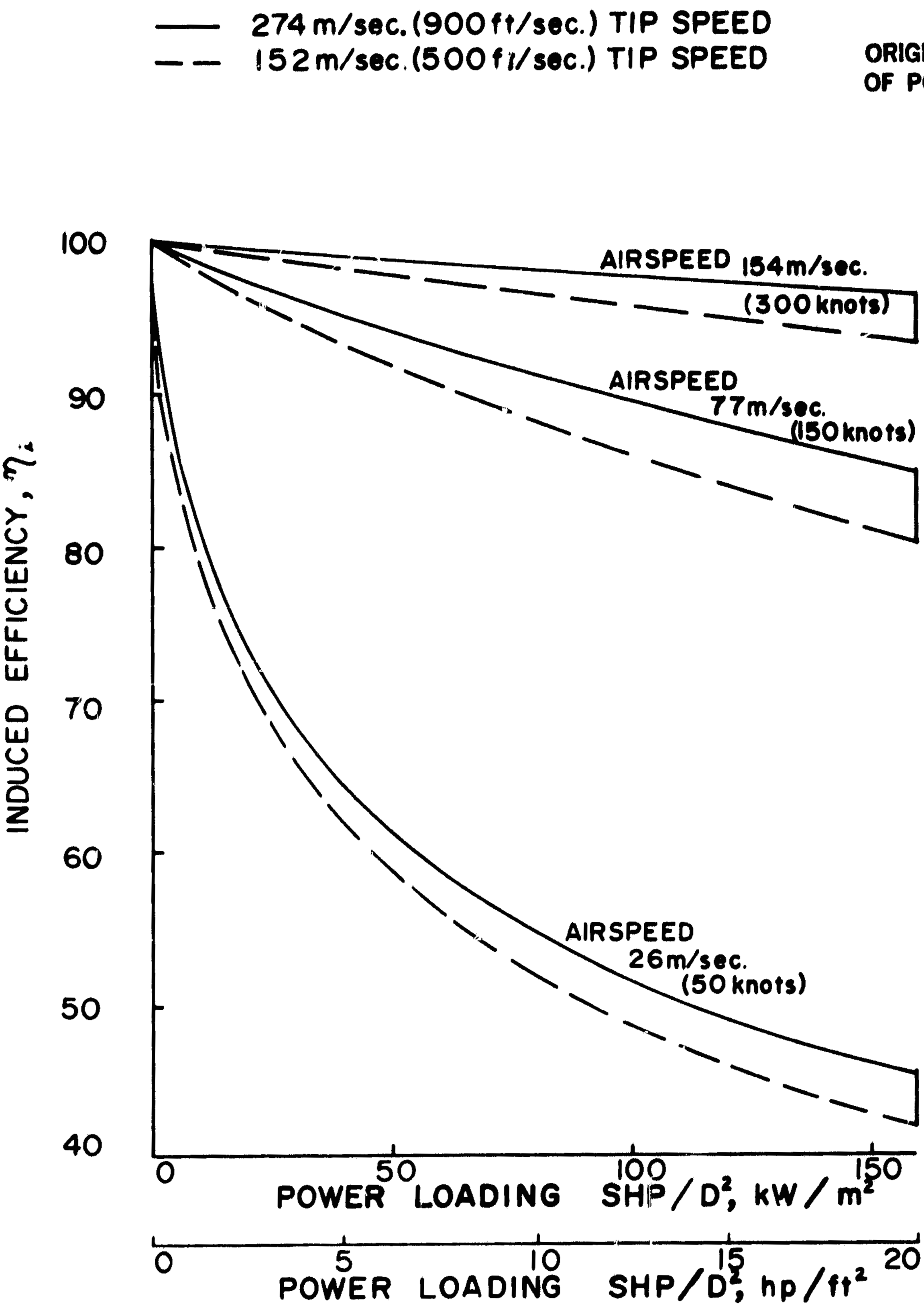
(b) 5 Bladed Propellers

Figure 6.- Continued



(c) 8 Bladed Propellers

Figure 6.- Continued



(d) Infinite Bladed Propeller

Figure 6.- Concluded

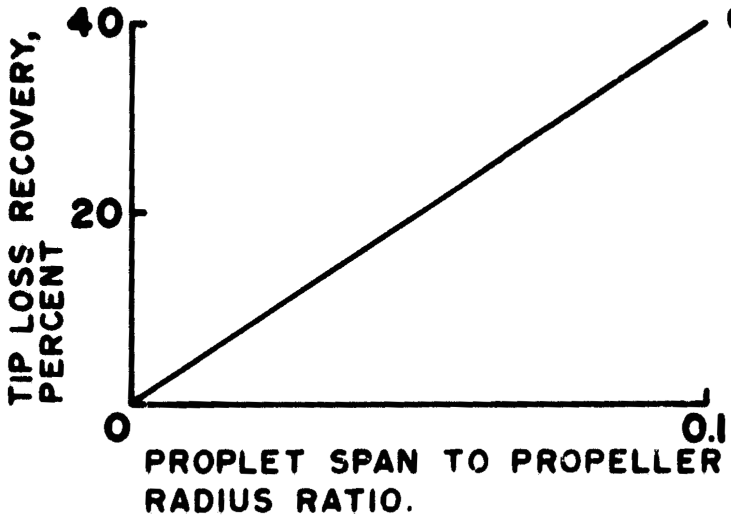


Figure 7.- Proplet performance evaluation.

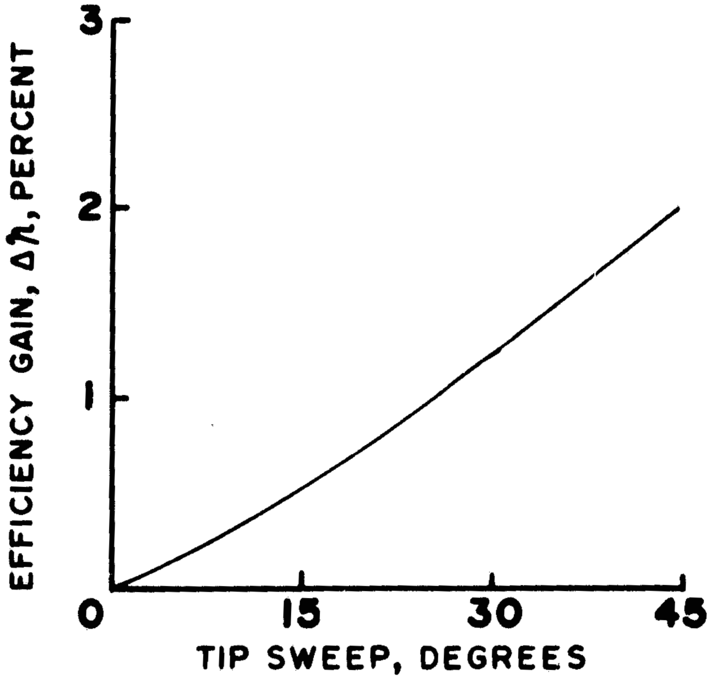


Figure 8.- Predicted effects of sweep on propeller performance.

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Figure 9.- Efficiency gain through reduction in thickness ratio.

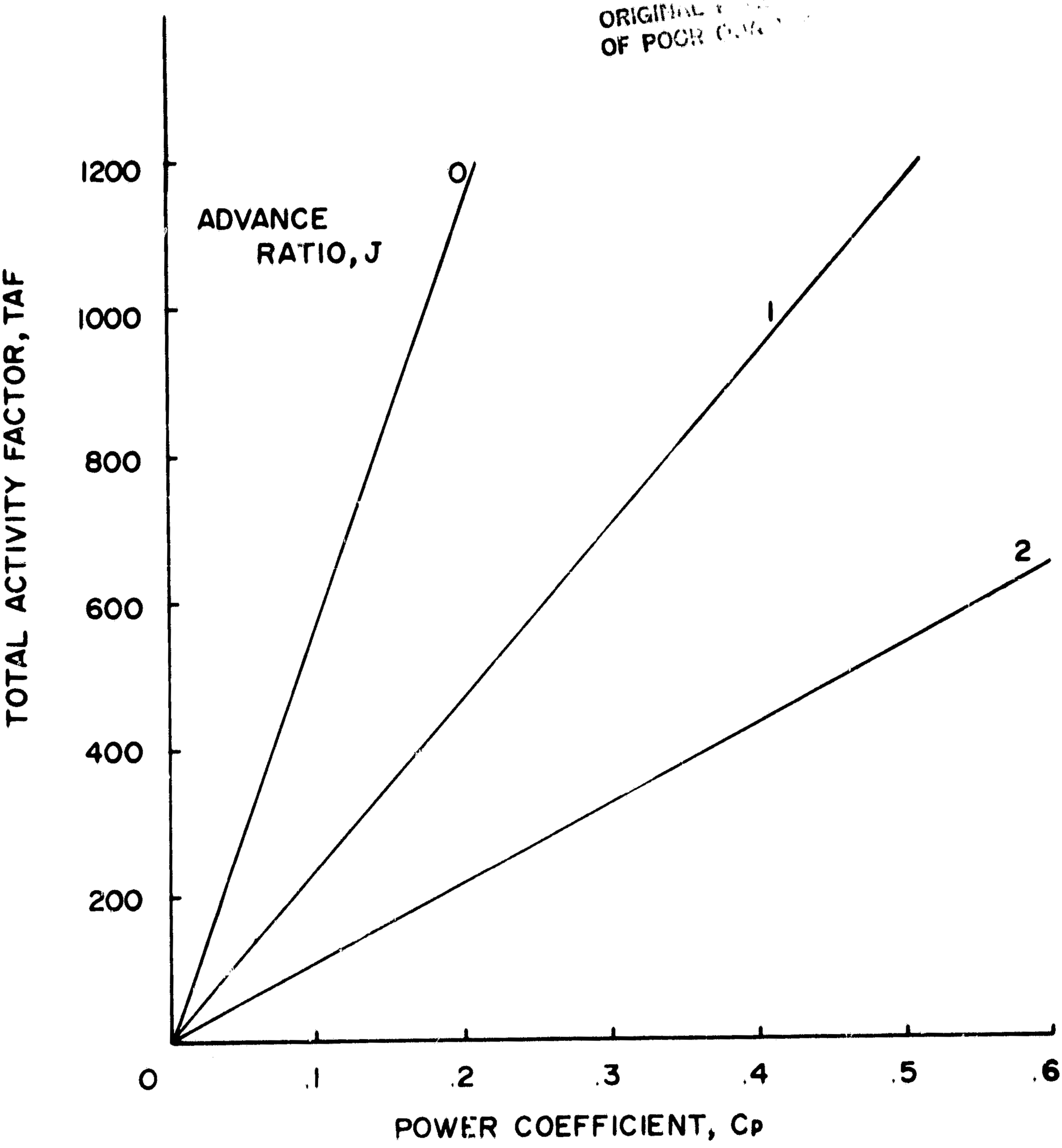

Figure 10.- Optimum total activity factor for given design advance ratio and power coefficient.

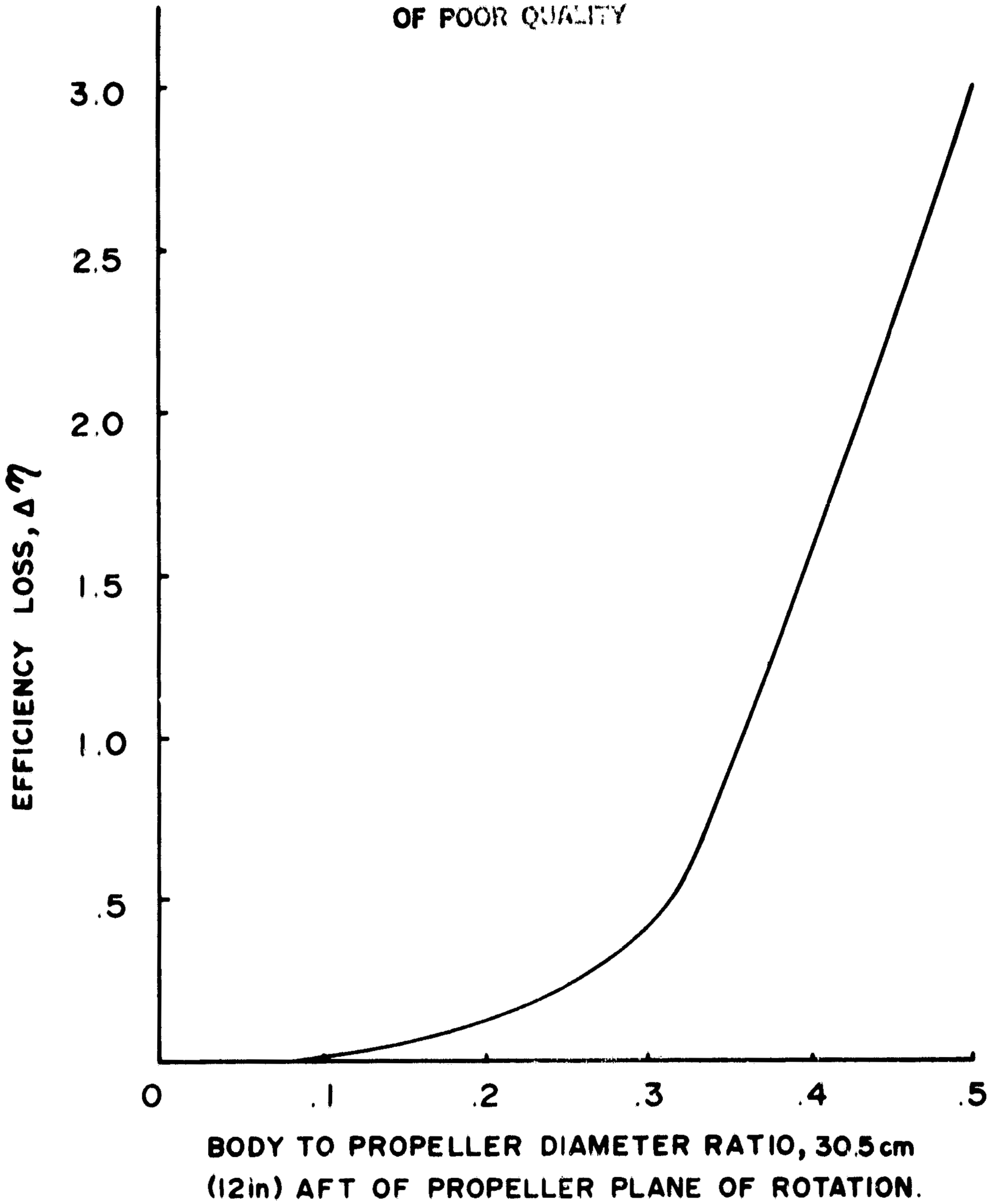

Figure 11.- Efficiency loss due to body blockage.

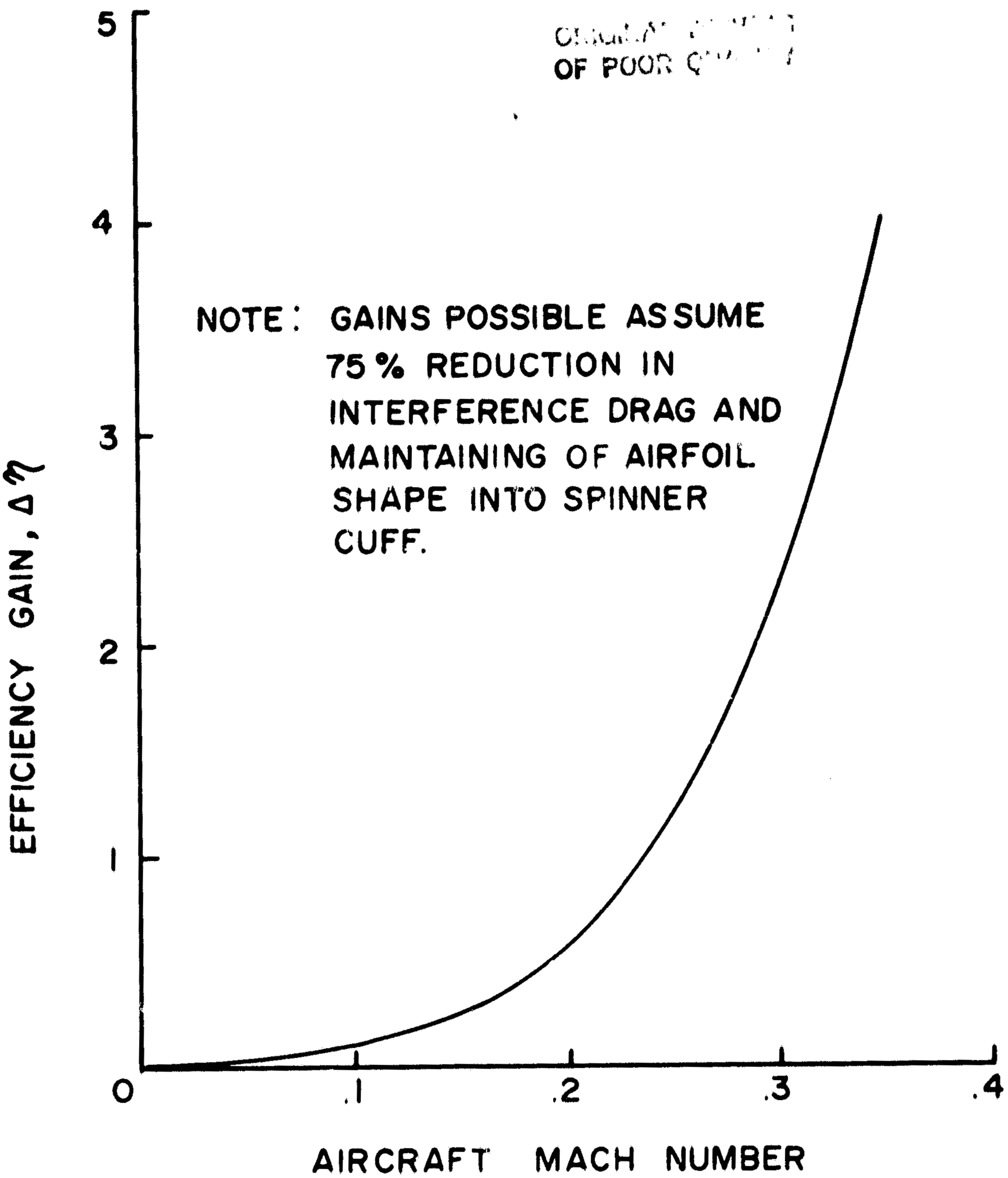

Figure 12.- Efficiency gains through reduction in spinner/shank interference drag.

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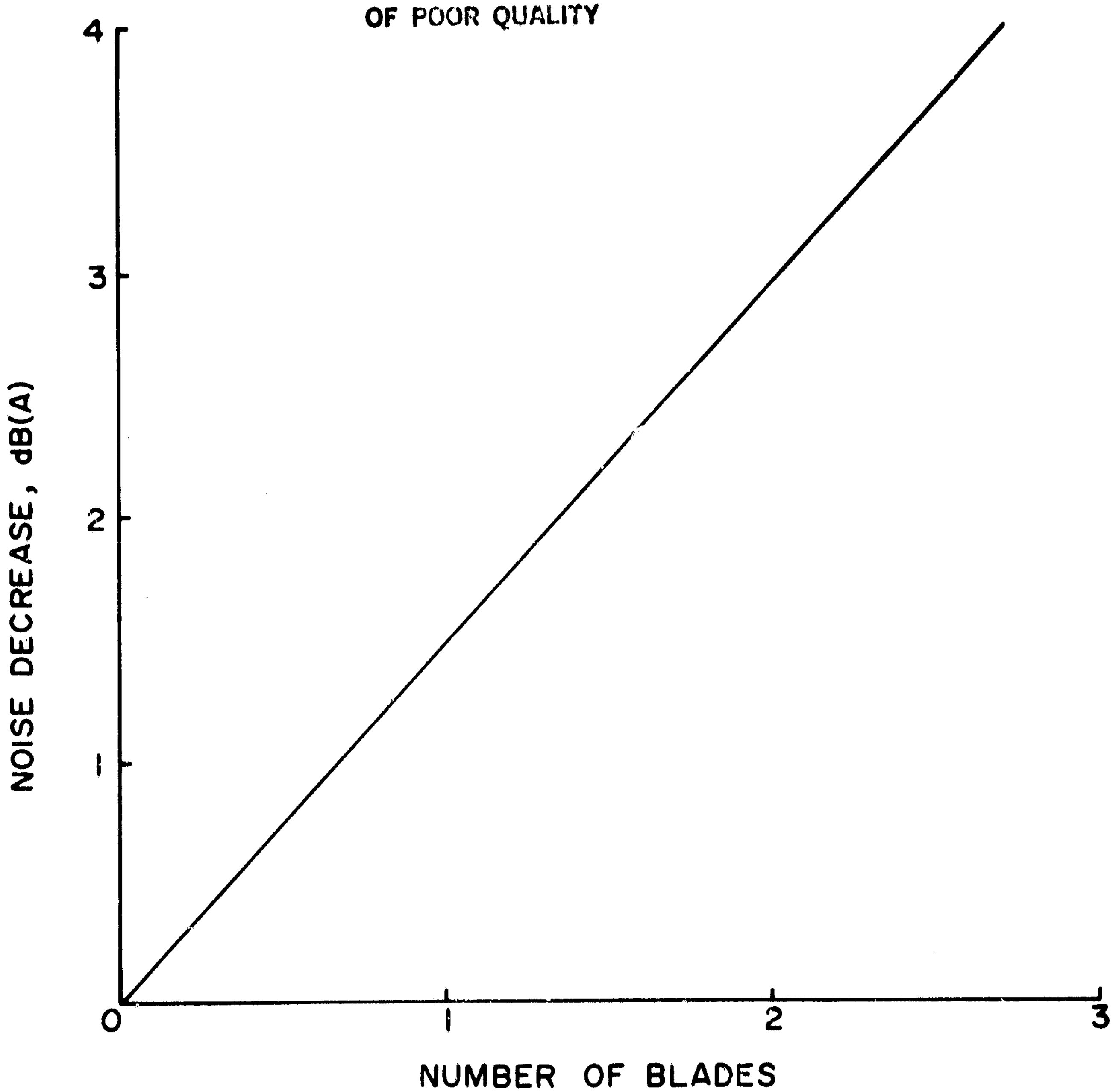

Figure 13.- Noise reduction through increase in number of blades.

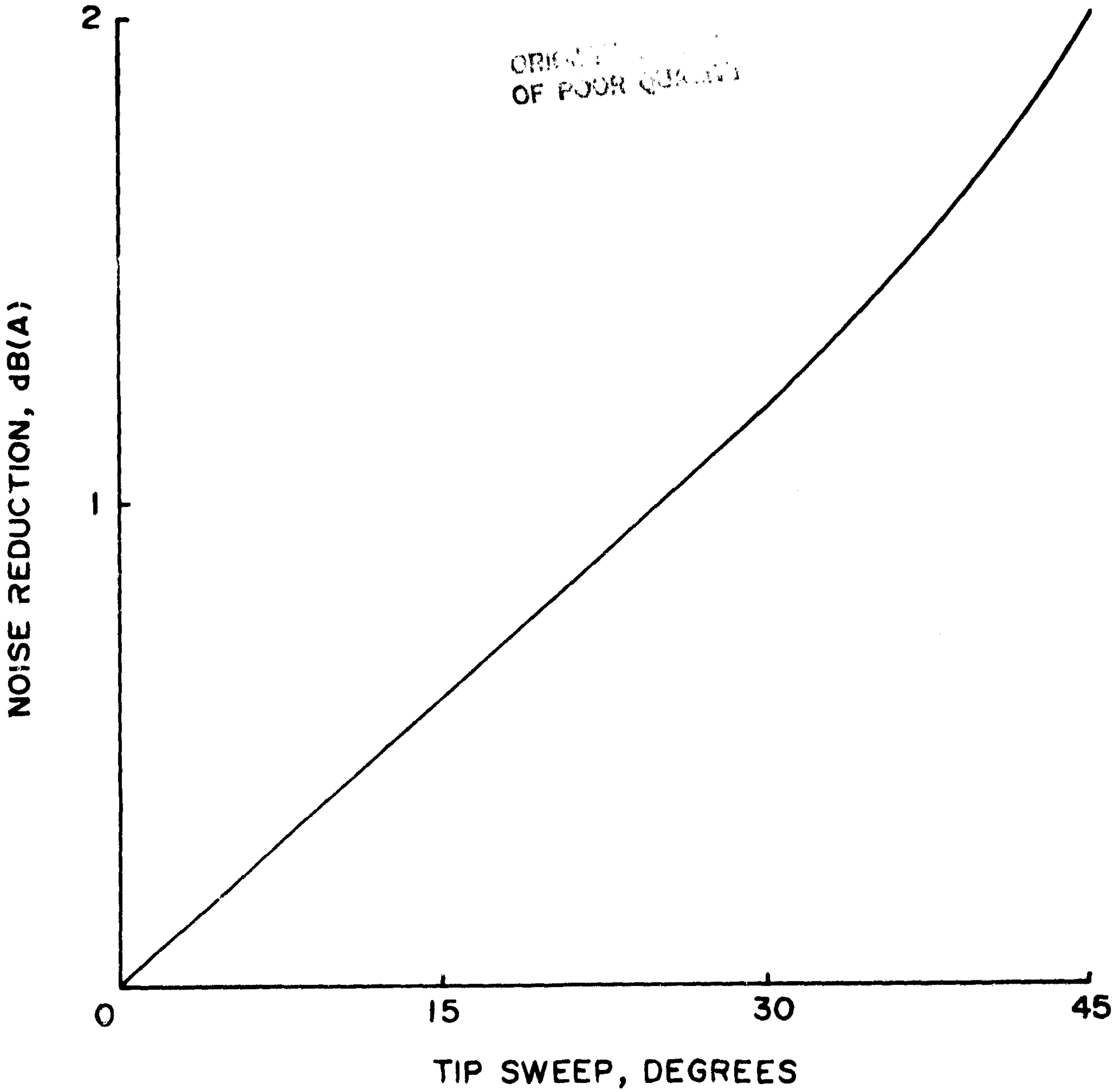

Figure 14.- Noise reduction with tip sweep.

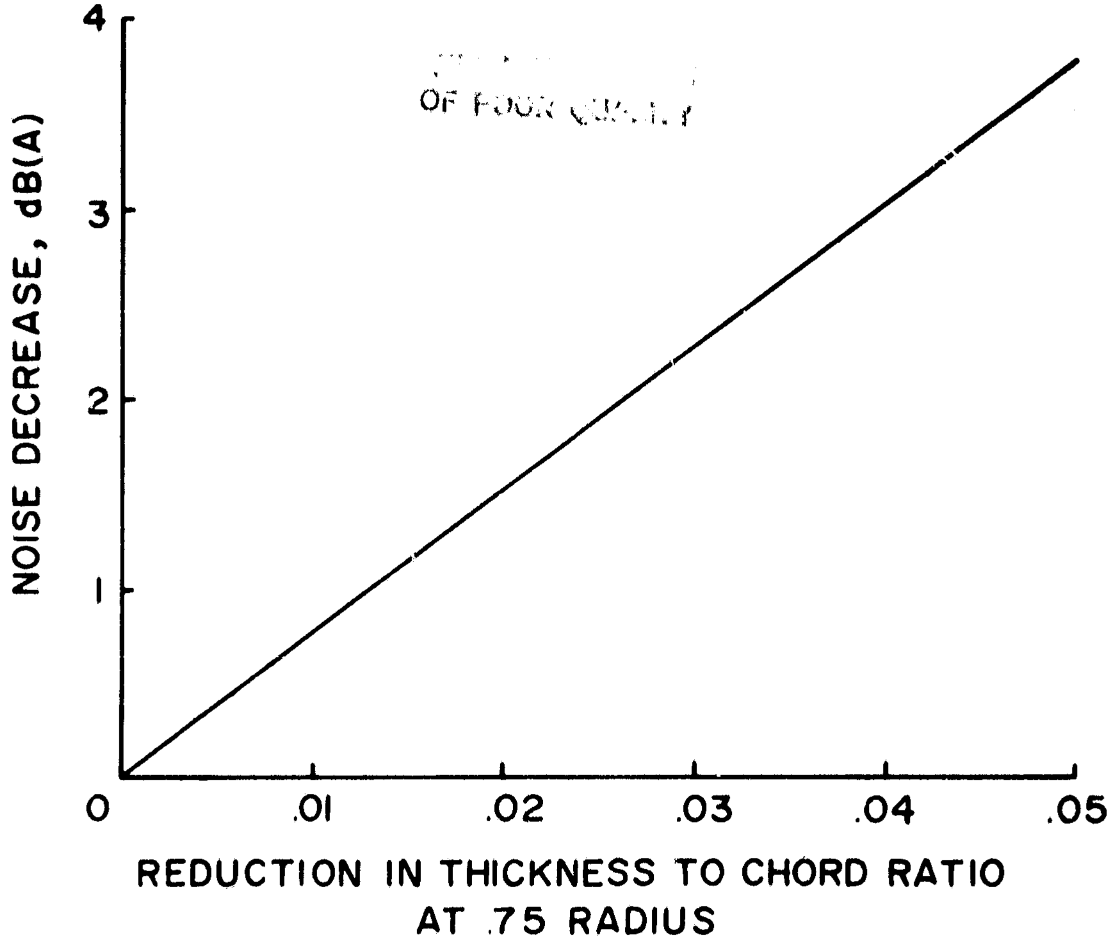

Figure 15.- Noise decrease through reduction in blade thickness.

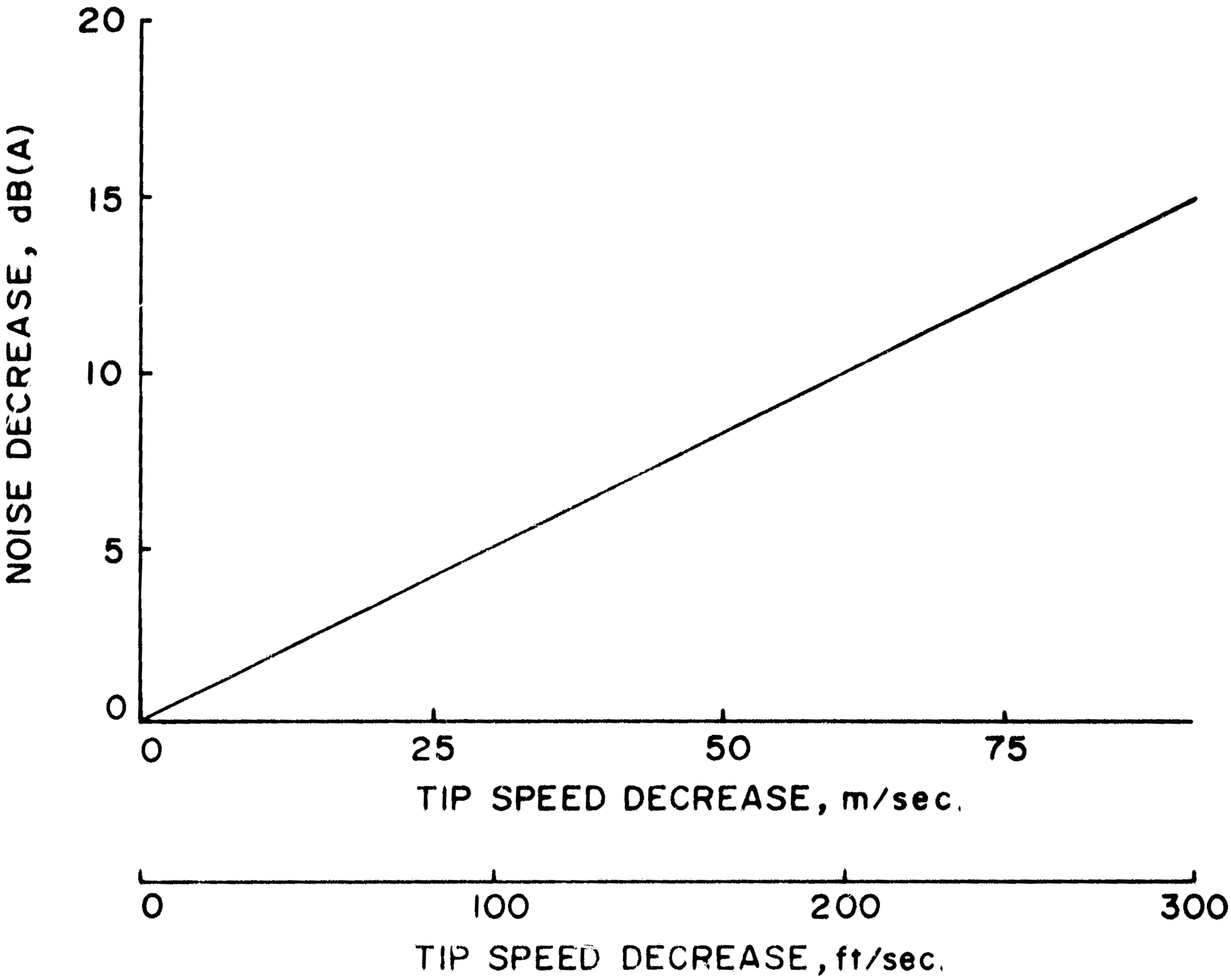

Figure 16.- Noise reduction with tip speed decrease.

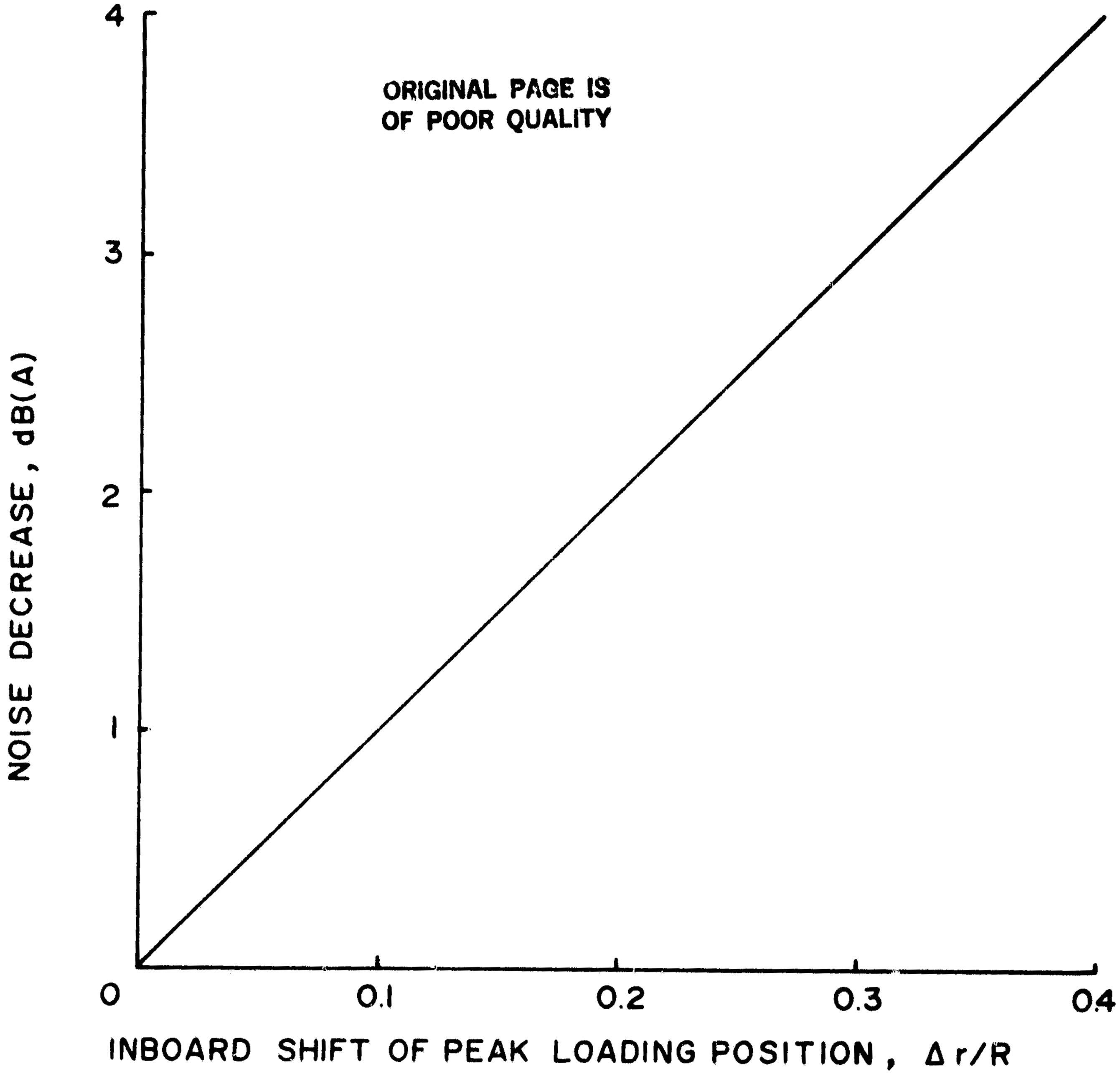

Figure 17.- Noise decrease with inboard shift of peak loading.

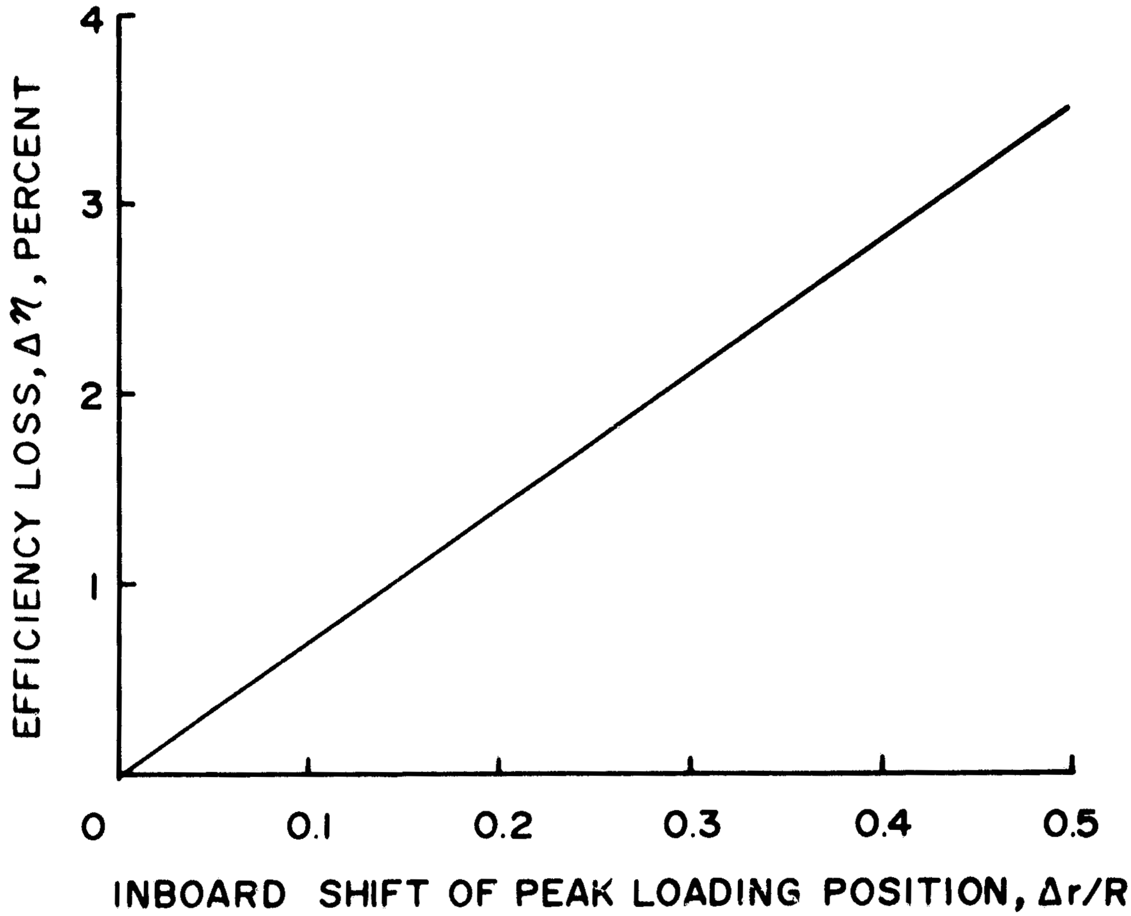

Figure 18.- Efficiency loss with inboard shift of peak loading.

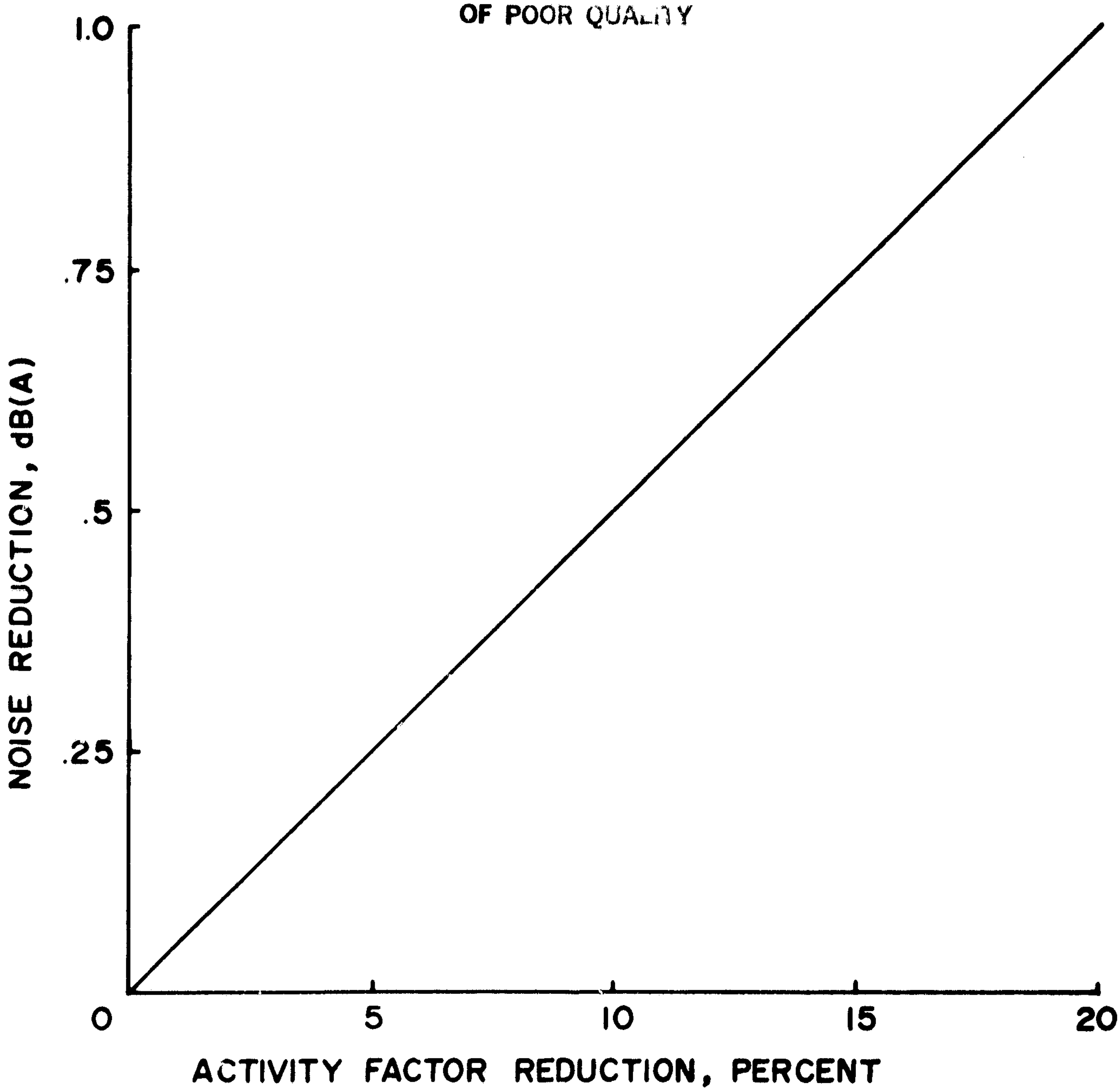

Figure 19. - Noise reduction through reduction in activity factor.

COMPOSITE ADVANTAGES	PROPELLER BENEFITS
GREATER STRENGTH	LOWER WEIGHT
LOWER DENSITY	IMPROVED PERFORMANCE
HIGHER MODULUS	LOWER NOISE
LOWER NOTCH SENSITIVITY	ENHANCED SAFETY MARGIN

Figure 20.- Benefits of composite materials.

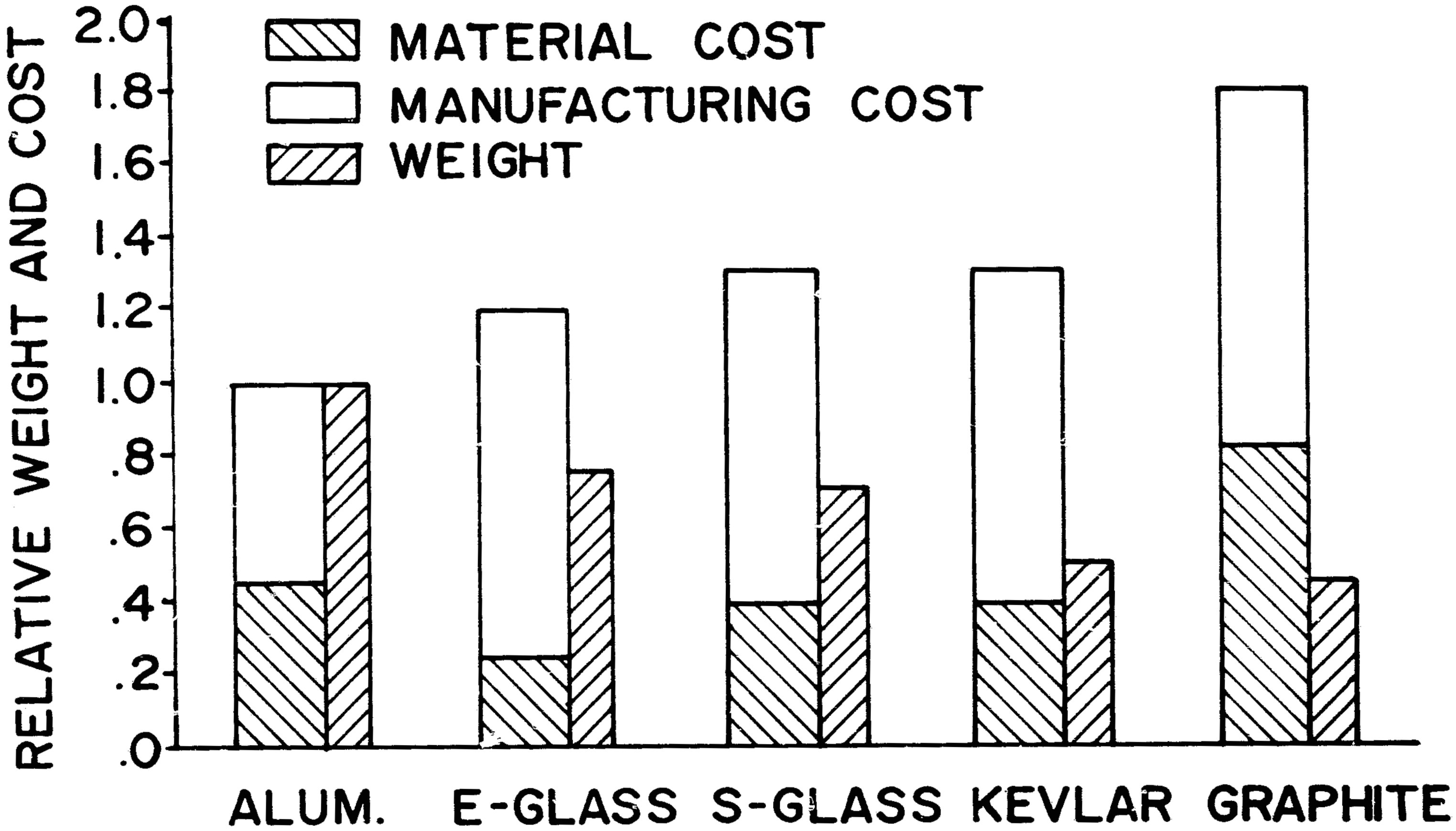

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Figure 21. - Blade weight and cost comparison.

(A) Aerodynamic	(B) Structural Design	(C) Environmental
diameter	frequencies	erosion
chord	materials	lightening
planform	fatigue life	repairability
twist	ultimate strength	
cross section	root end attachment	
	balance	
	manufacturing process	
	cost	

Figure 22.- Design criteria.

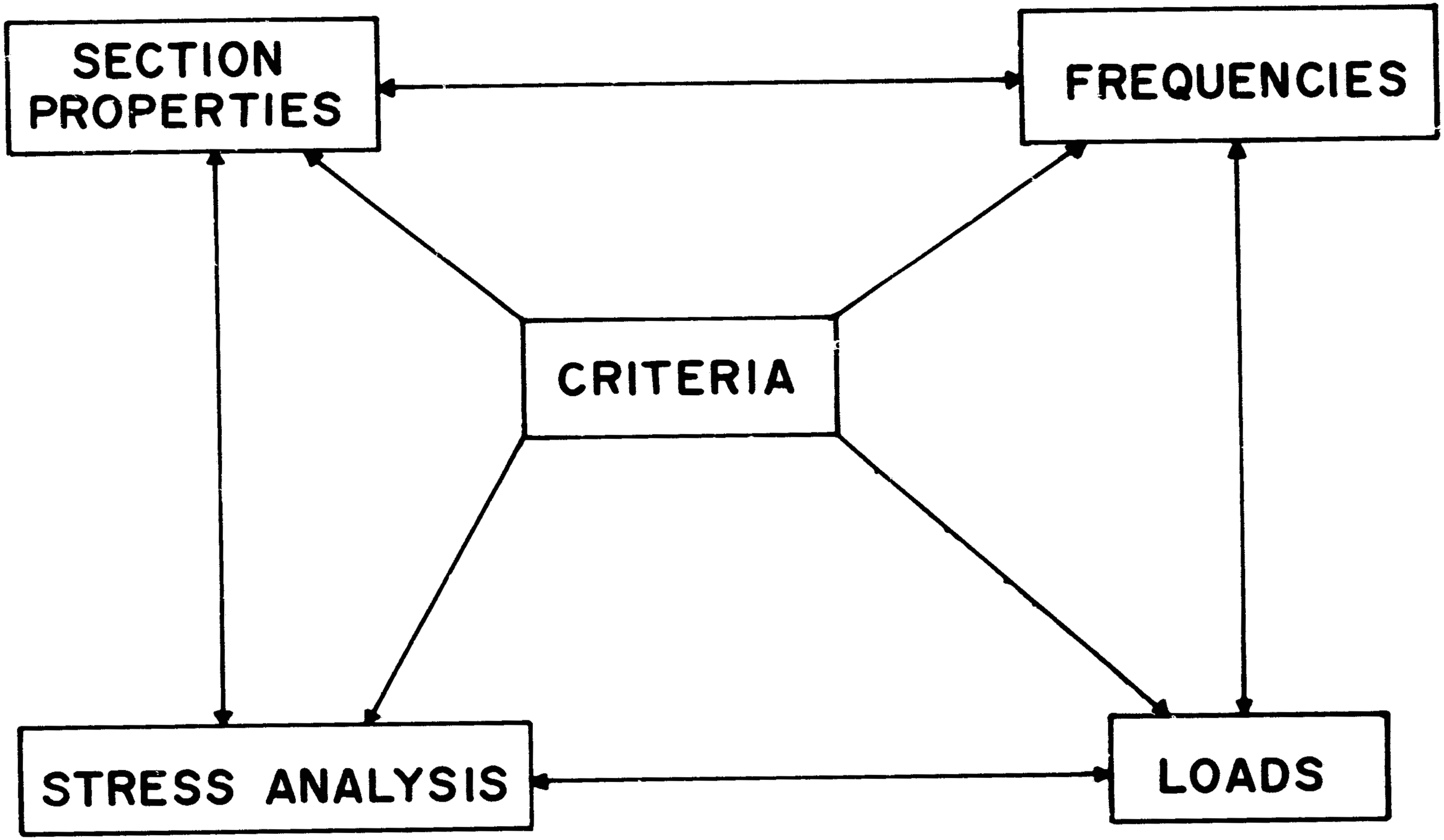


Figure 23.- Iterative process to assure blade structural adequacy.

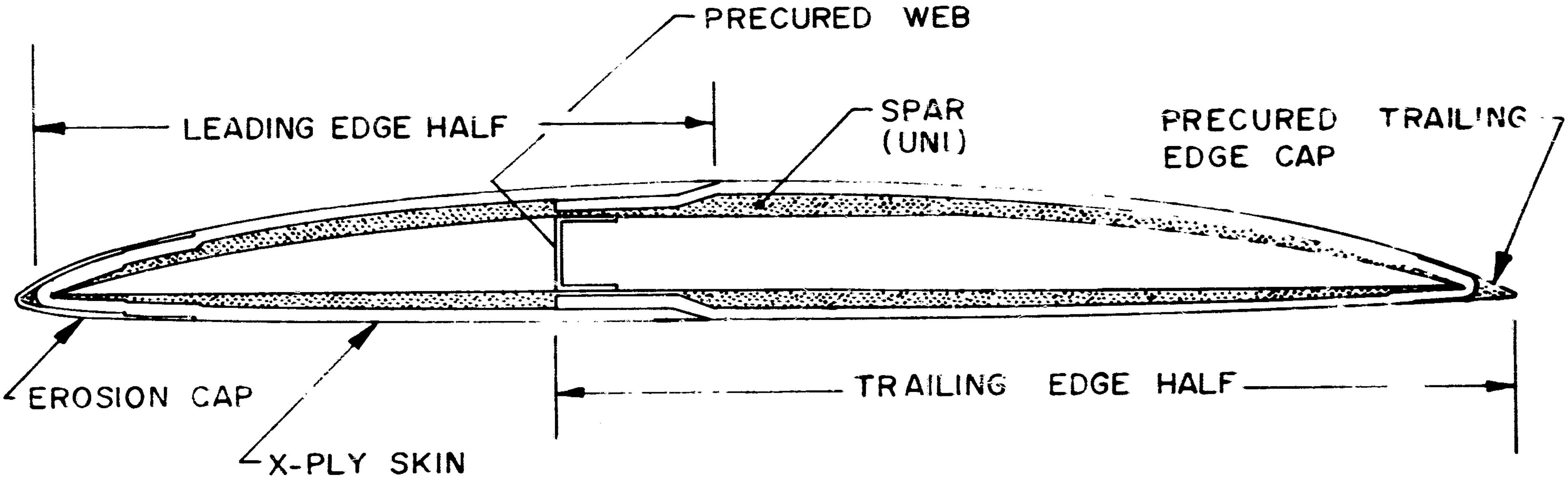


Figure 24.- Precured Leading and Trailing Halves.

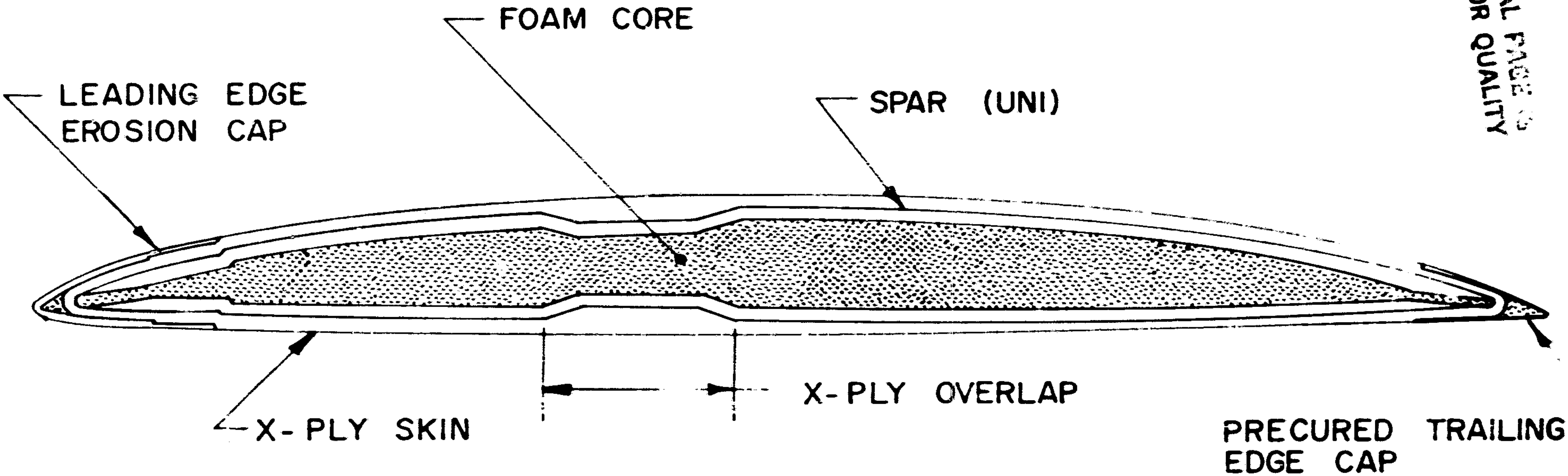


Figure 25.- Foam Core

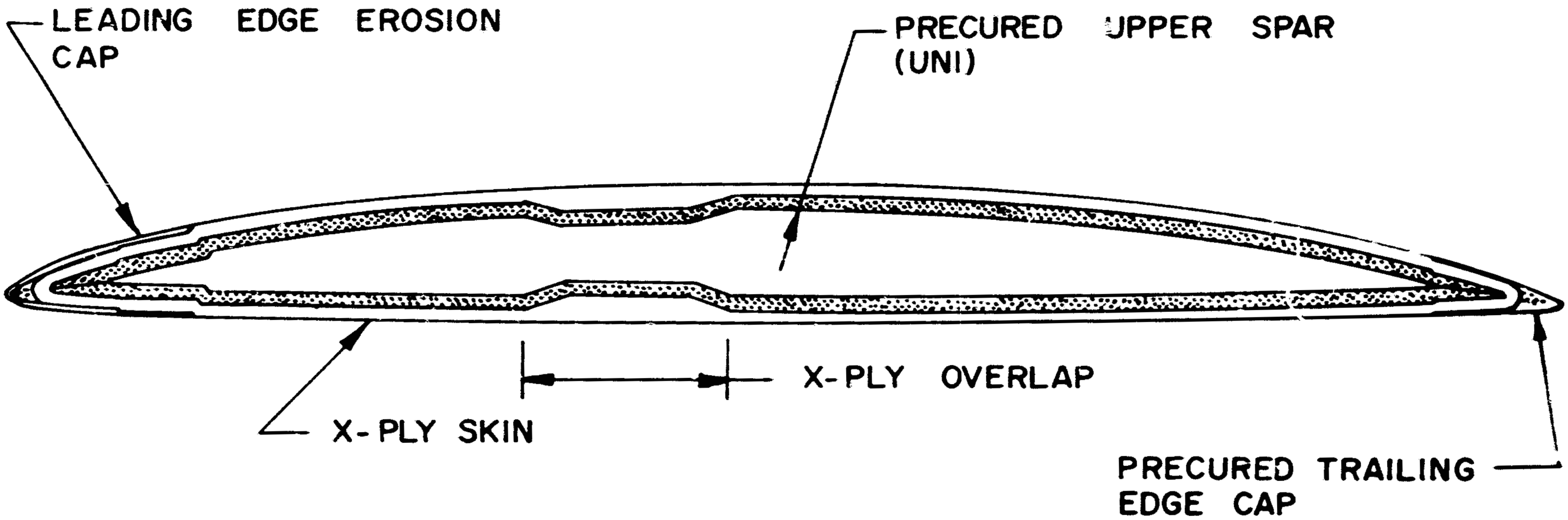


Figure 26.- Precured Upper and Lower Spars.

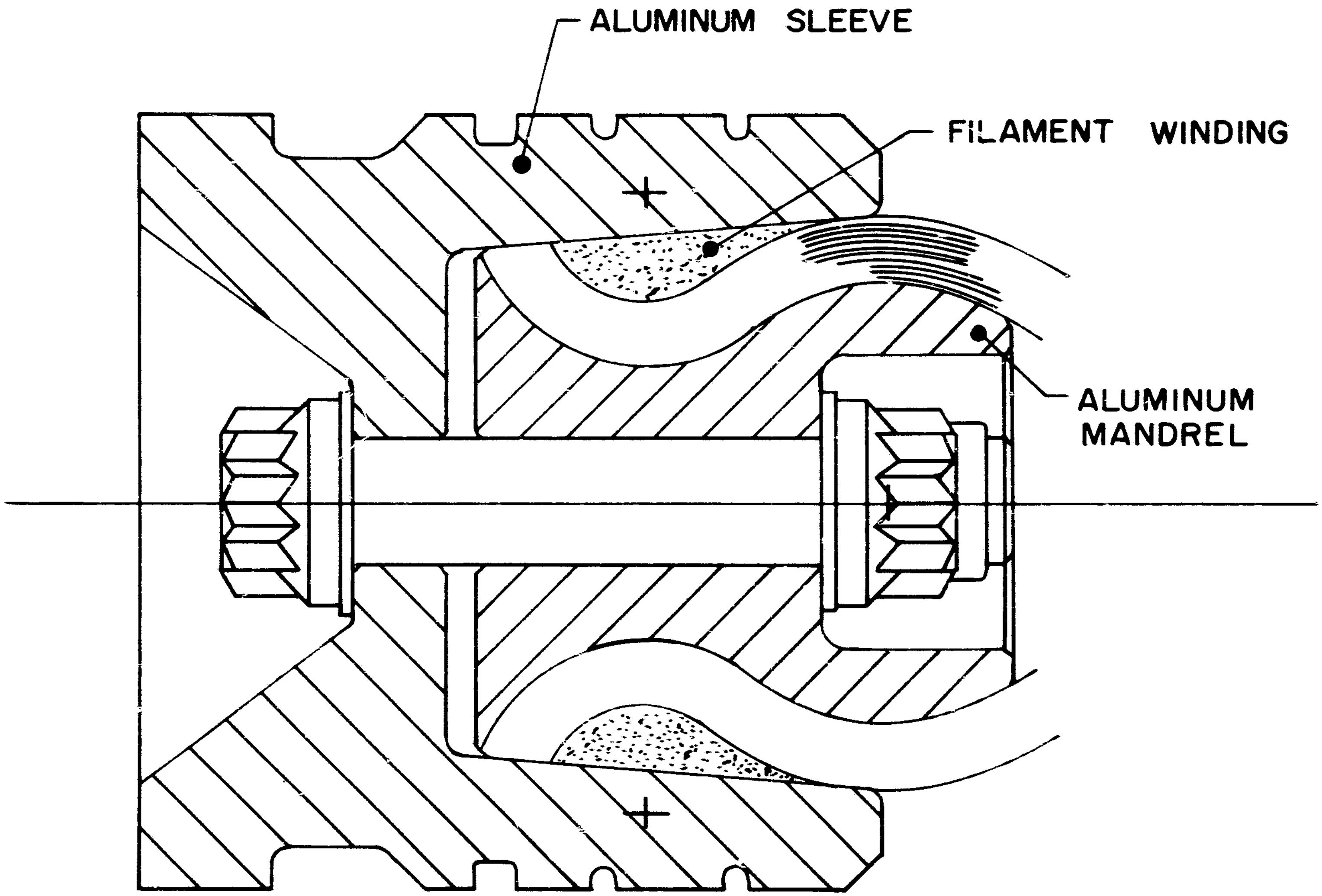


Figure 27.- Coke Bottle Root End.

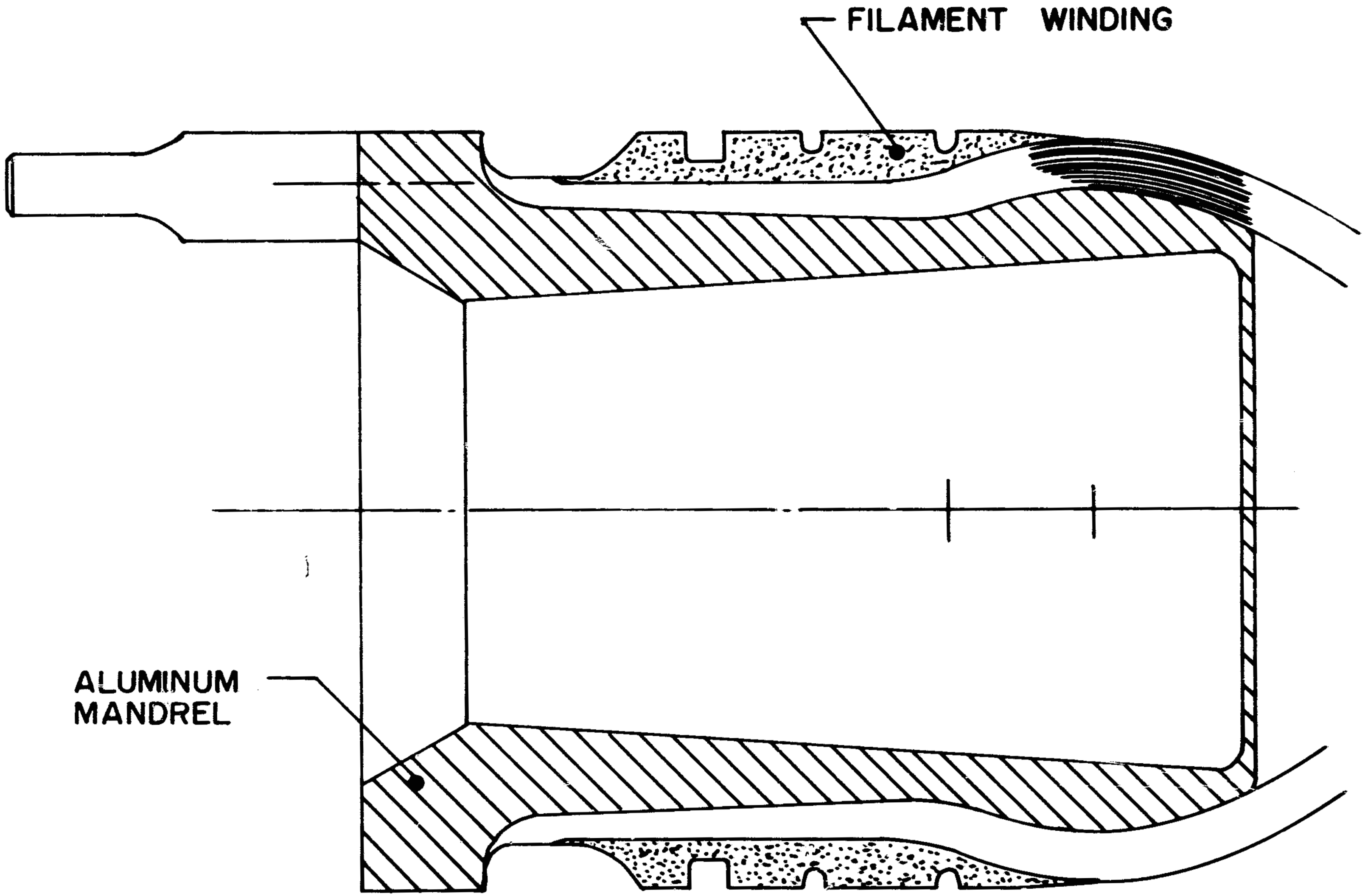


Figure 28.- Hybrid Root End.

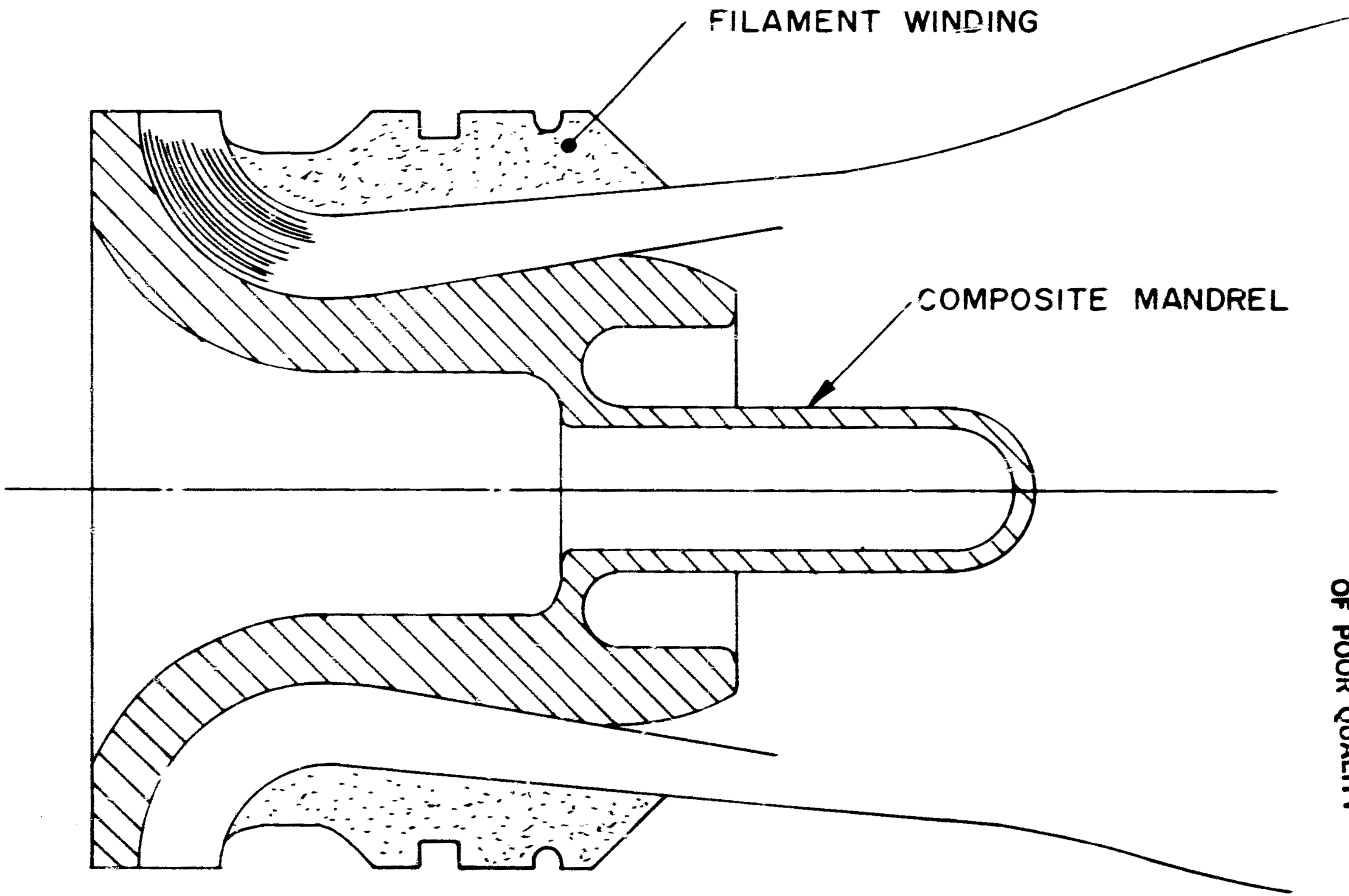
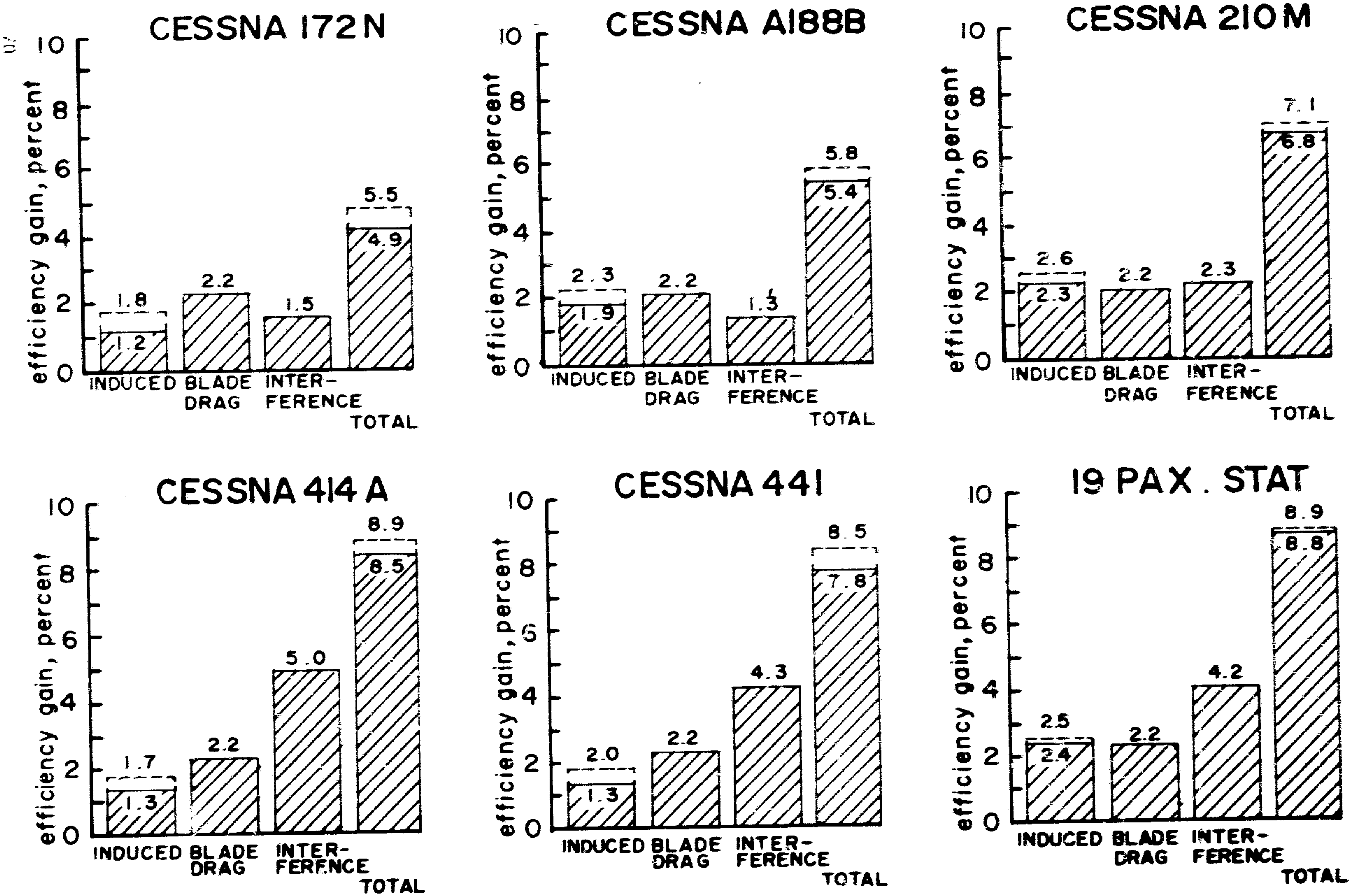


Figure 29.- All Composite Root End.



----- BOTH BASELINE AND ADVANCED CONFIGURATIONS MEET FAR36.

——— BASELINE MEETS FAR 36; ADVANCED CONFIGURATIONS MEET FAR36-5dB(A).

Figure 30.- Potential cruise performance gains, two hour cruise mission.

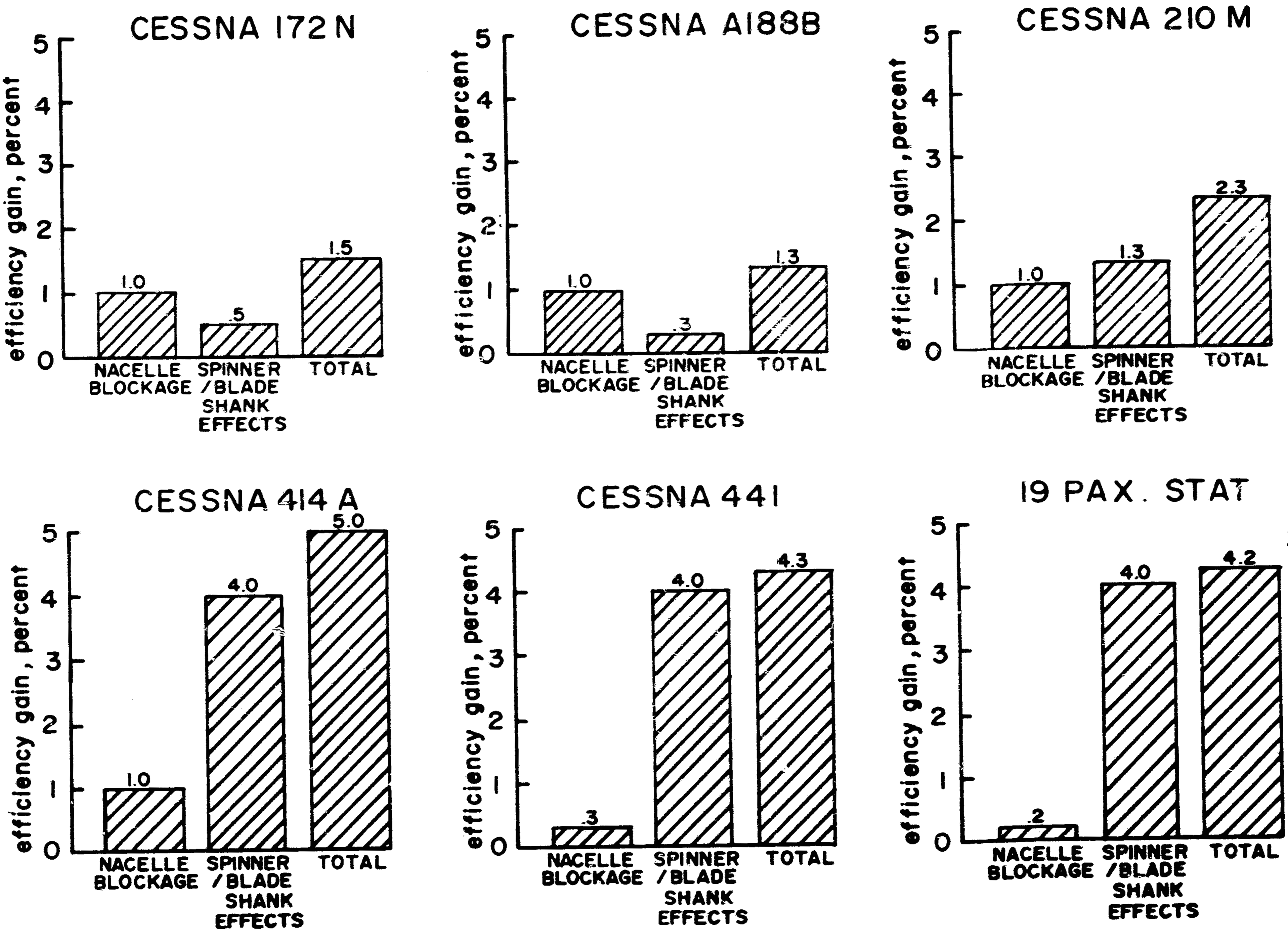


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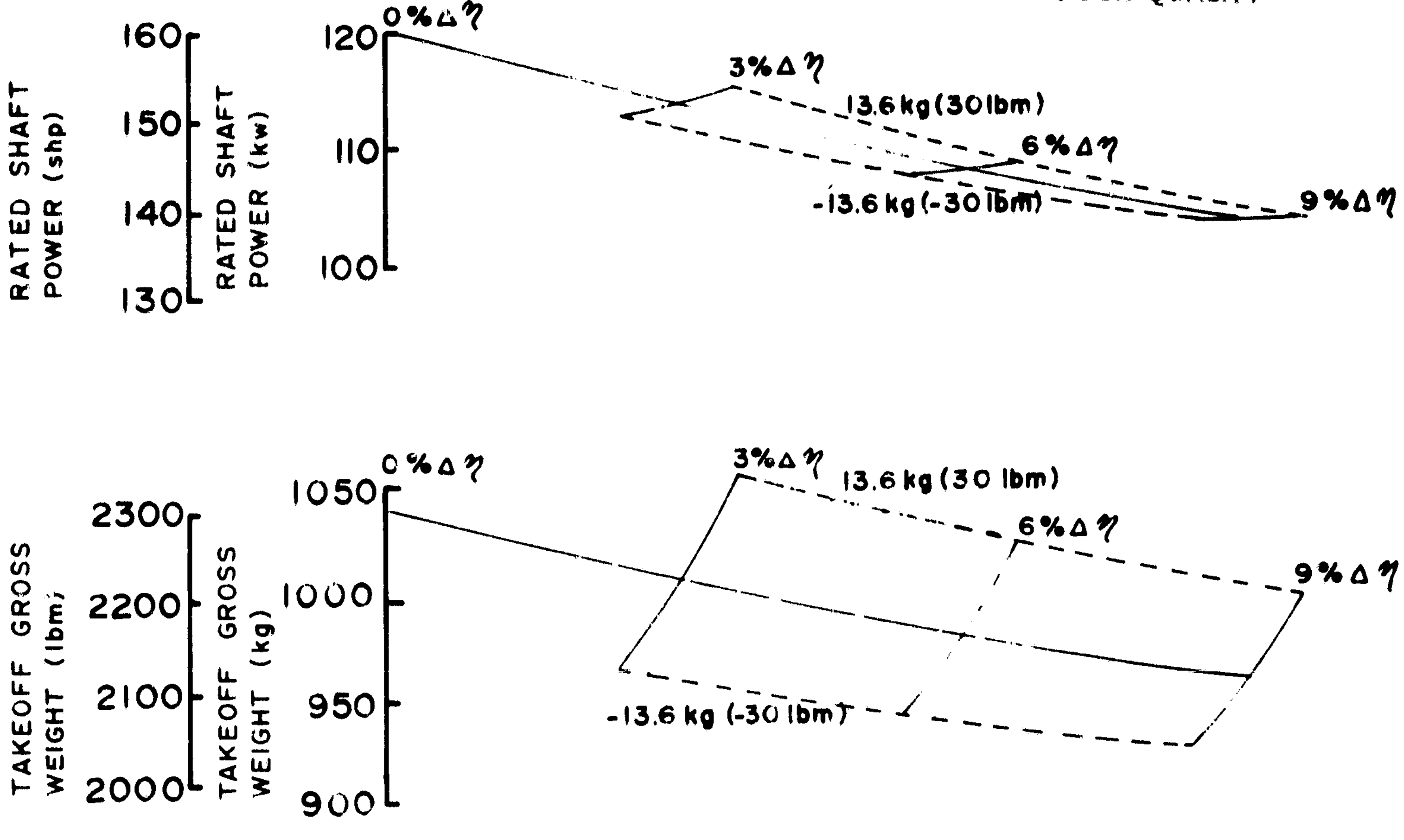
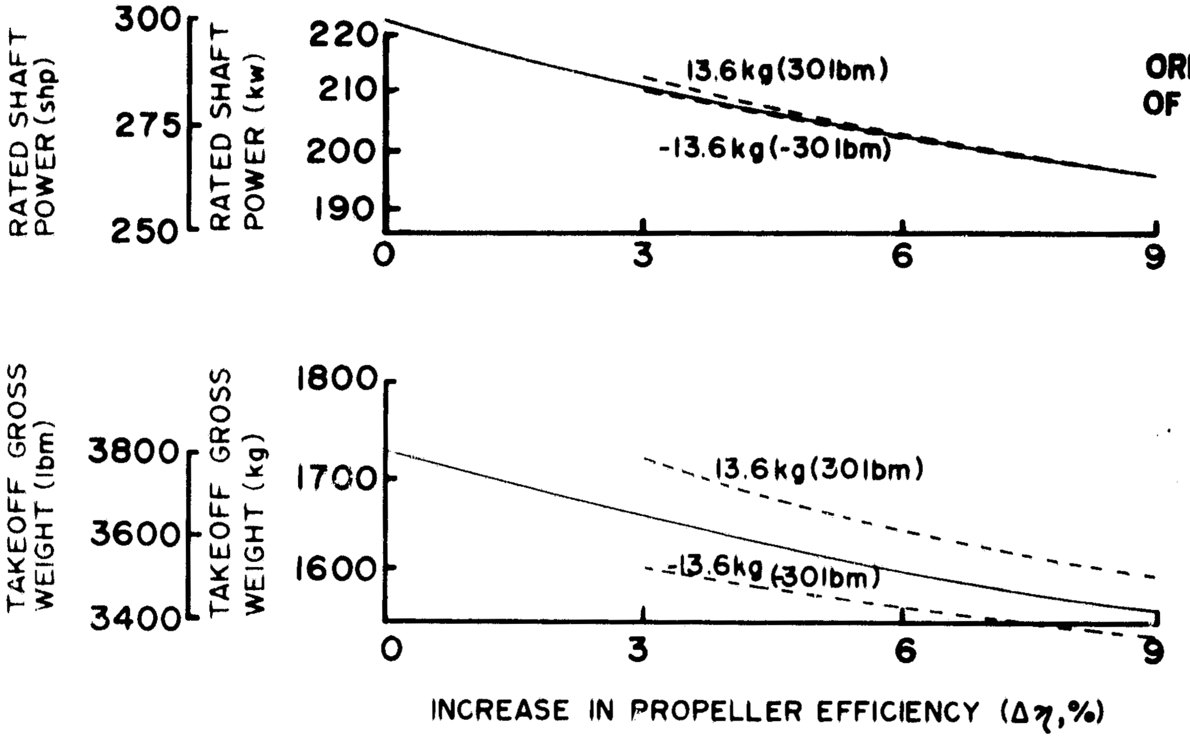
Figure 31. - Potential performance gains from interference effects.

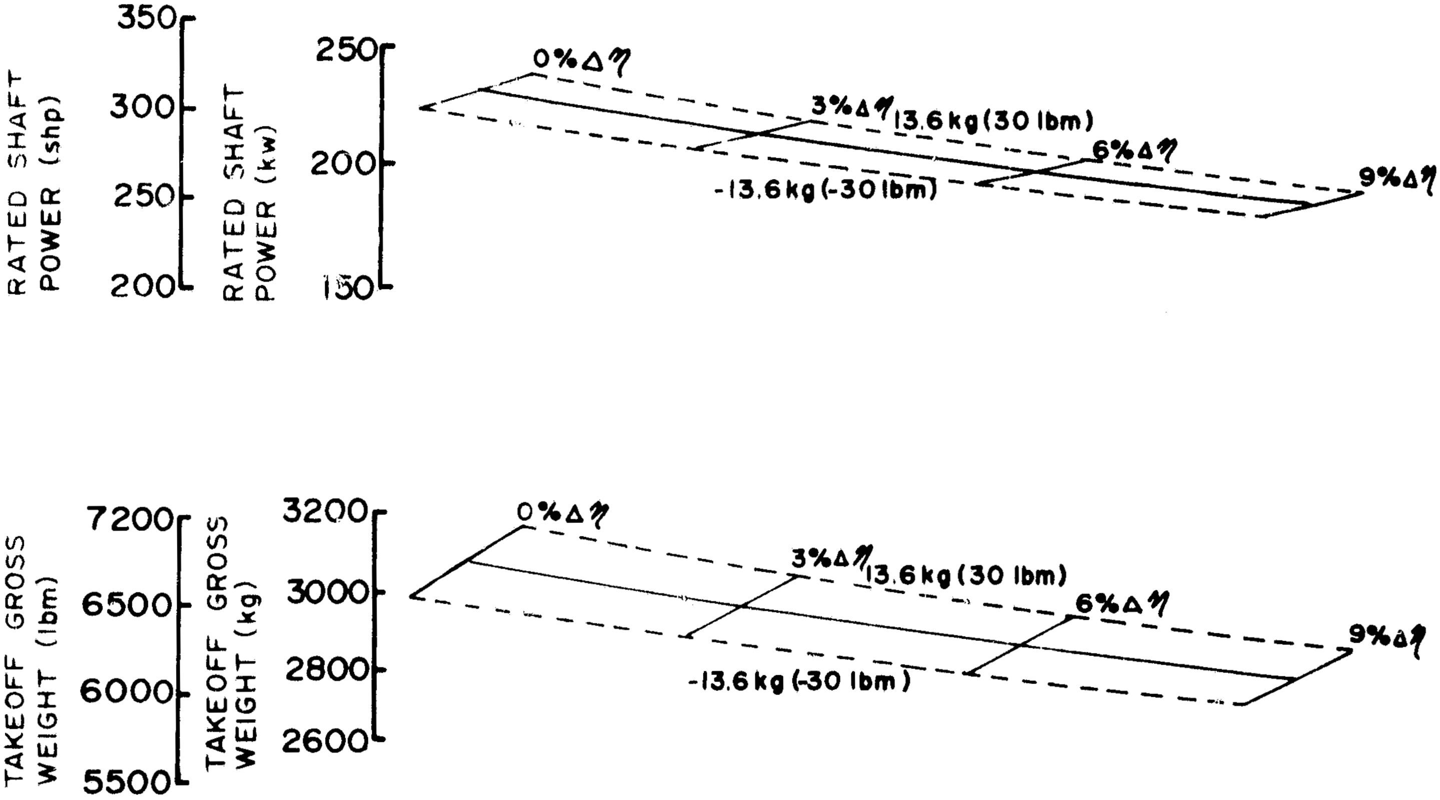


(a) Cessna 172N

Figure 32.- Effect of propeller weight and efficiency on aircraft characteristics for a two hour cruise mission.

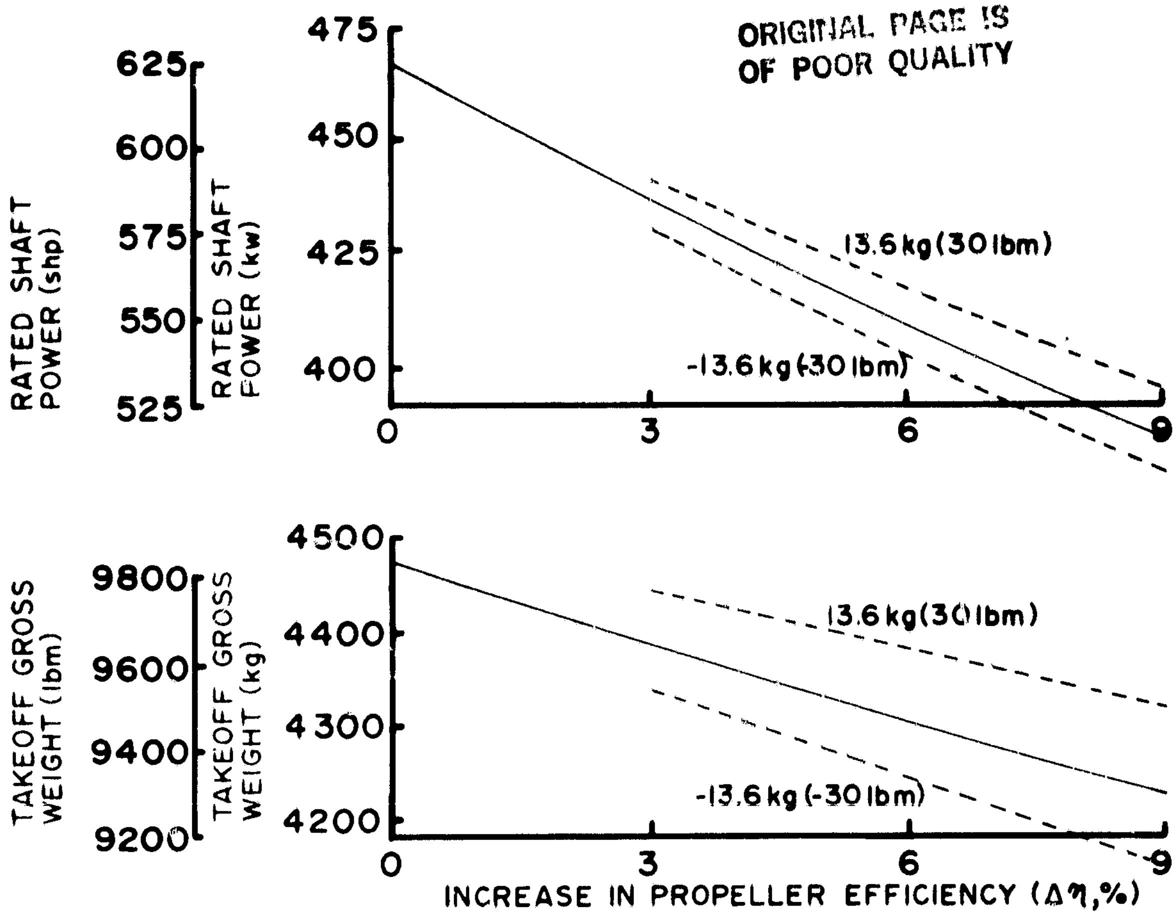


(b) Cessna 210M

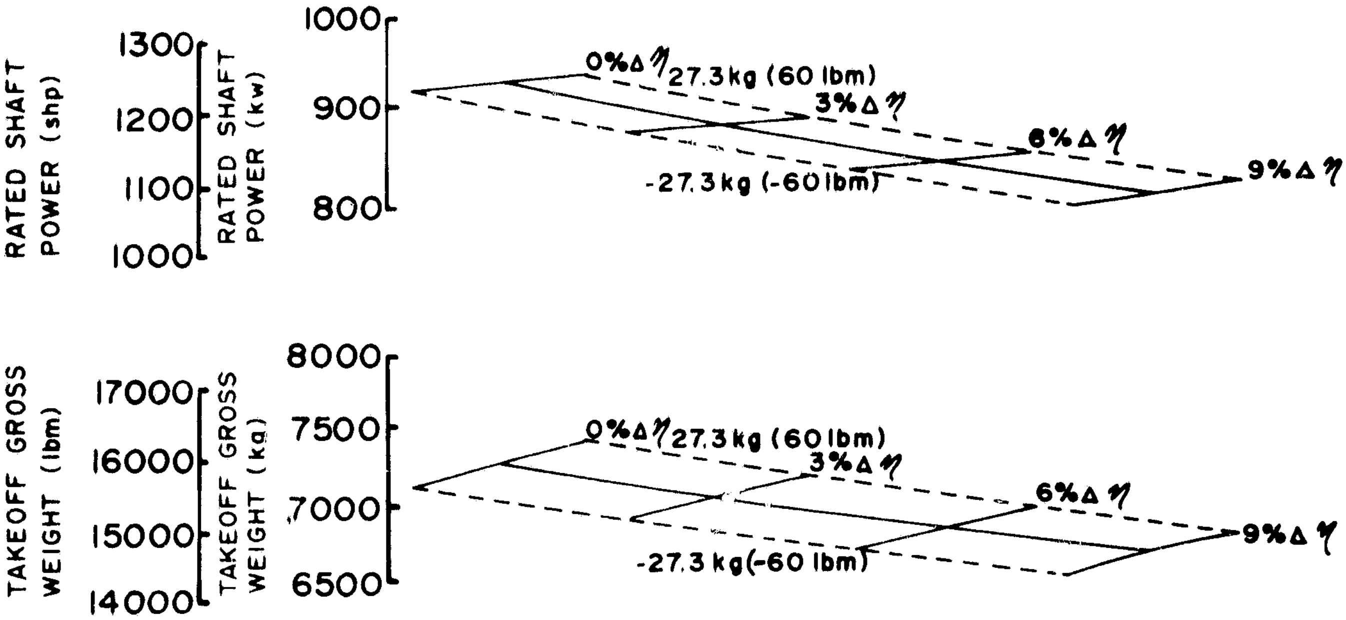


(c) Cessna 414 A

Figure 32.- Continued.



(d) Cessna 441



(e) 19 passenger STAT aircraft

Figure 32.- Concluded.

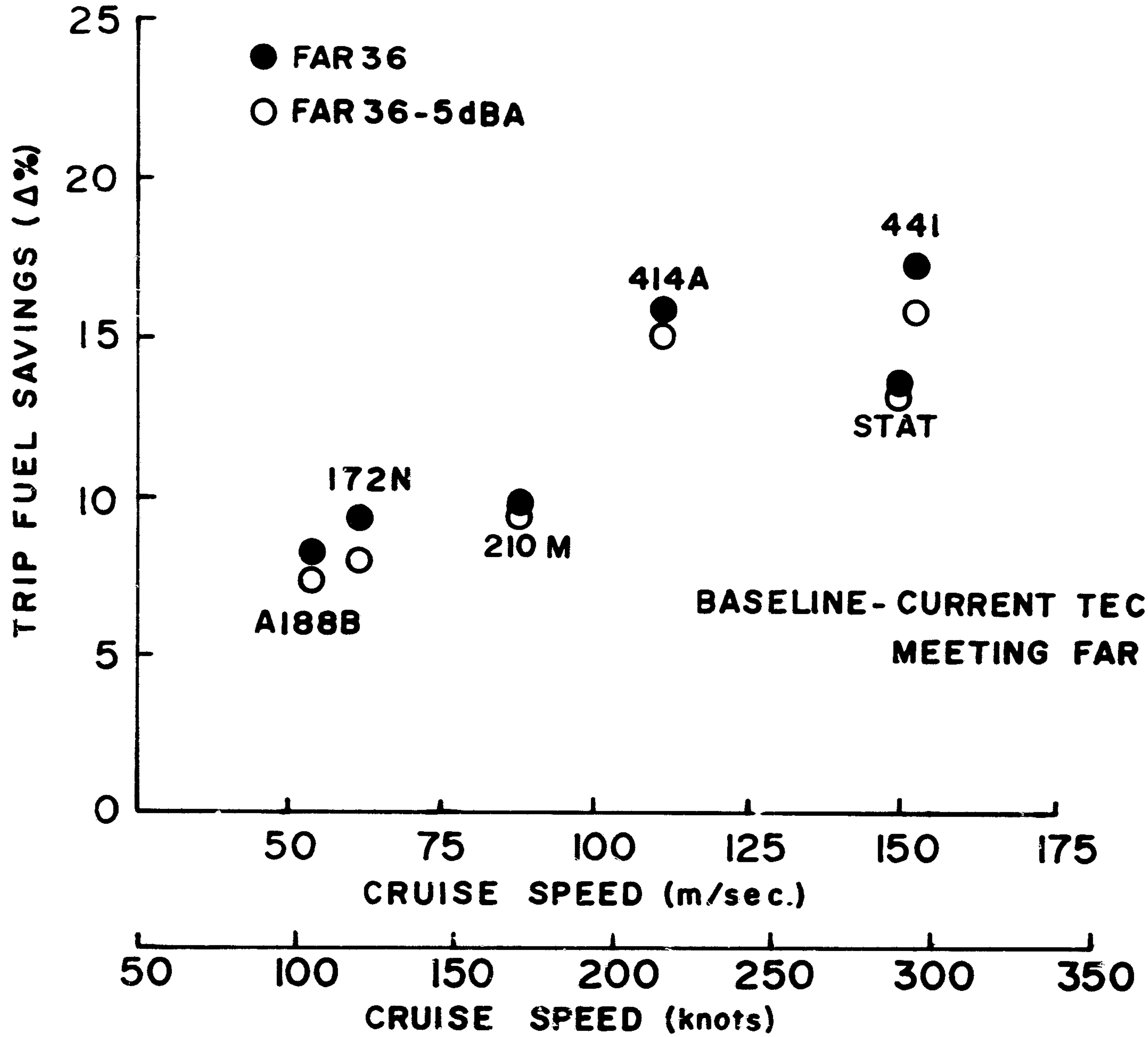


Figure 33.- Potential trip fuel savings.

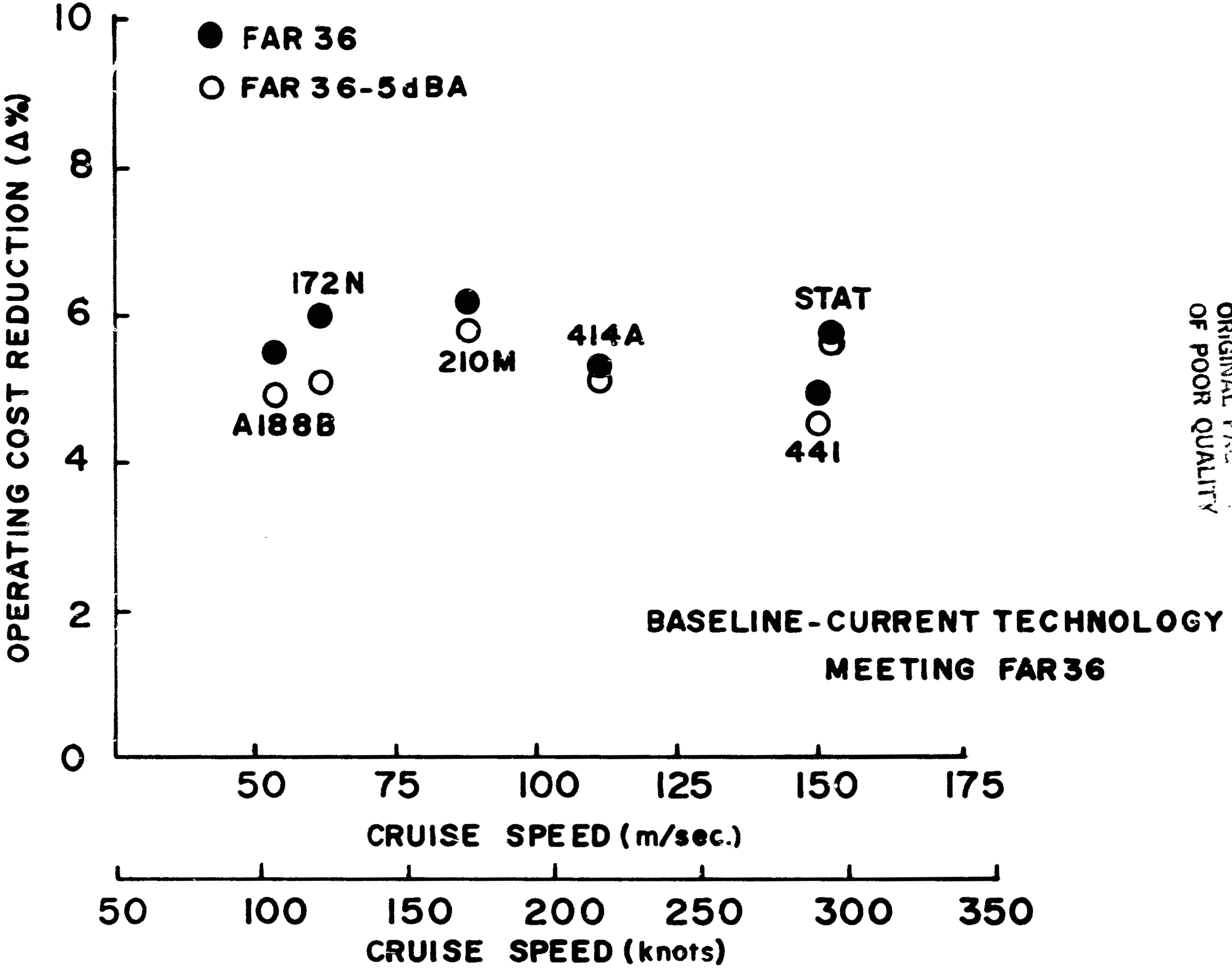


Figure 34 .- Potential operating cost reduction.

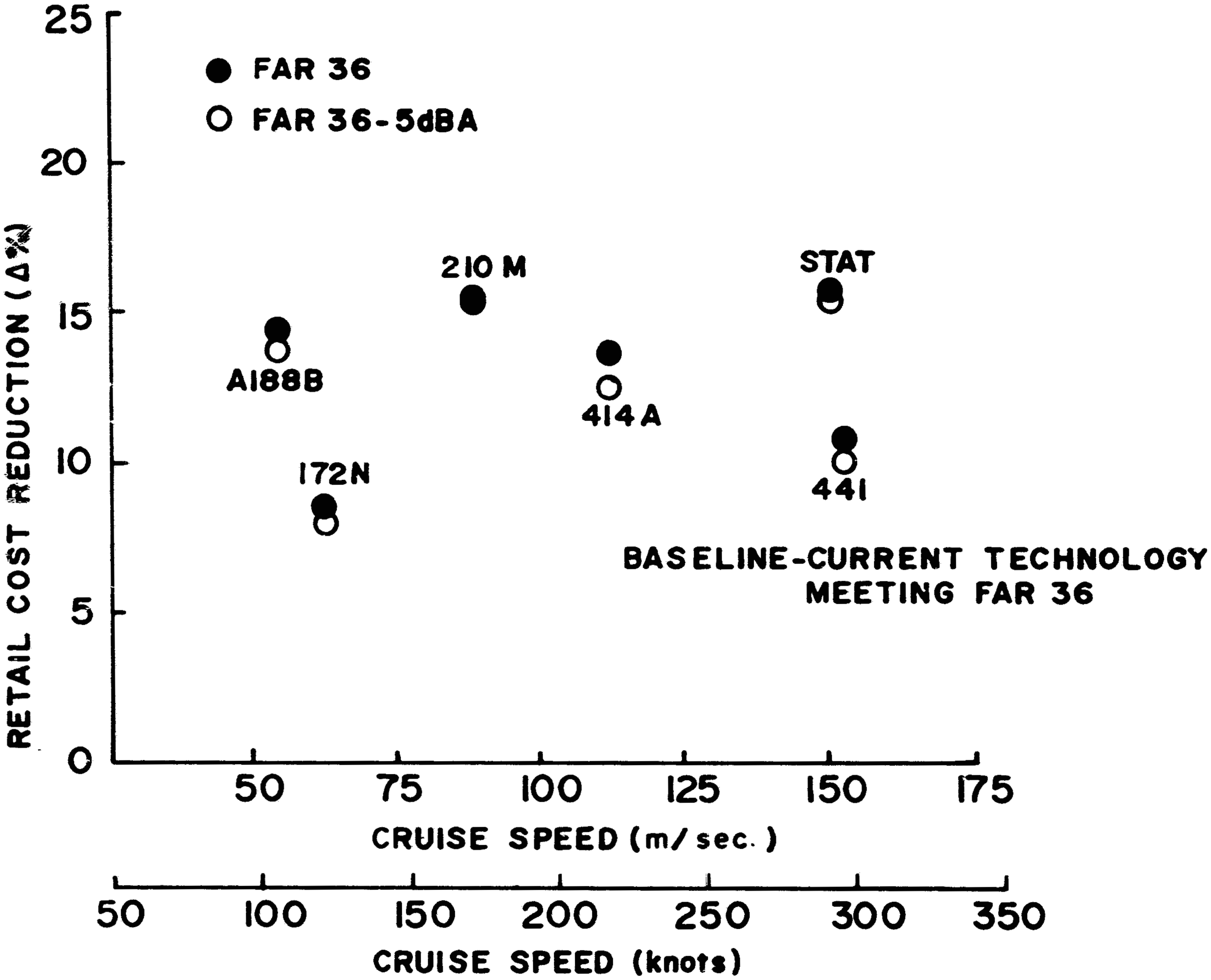


Figure 35.- Potential aircraft retail cost reduction.

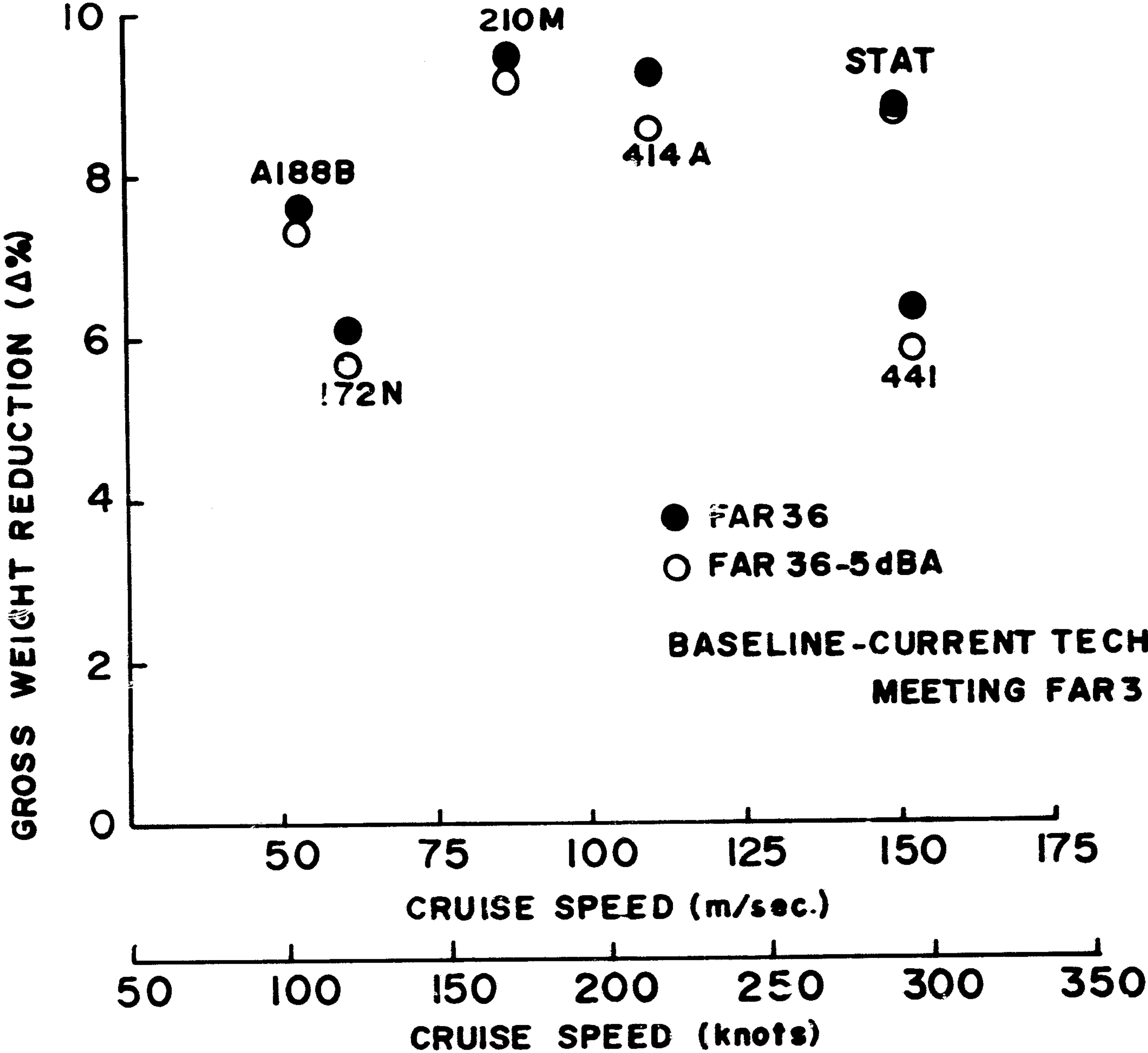


Figure 36.- Potential gross weight reduction.

- TECHNOLOGY DEVELOPMENT

  AERODYNAMICS

  ACOUSTICS

  AEROELASTICS

  COMPOSITES

- TECHNOLOGY INTEGRATION & VERIFICATION

Figure 37.- Recommended technology program.