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Small Transport Aircraft Technology Propeller Study

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of United Technologies Corporation

Prepared for
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16. Abstract

A study to define potential benefits of advanced technology propellers for 1985-1990 STAT commuter airplanes was completed. Two baselines, a Convair, 30 passenger, 0.47 Mach number airplane and a Lockheed, 50 passenger, 0.70 Mach number airplane, were selected from NASA-Ames sponsored airframe contracts. Parametric performance, noise level, weight and cost trends for propellers with varying number of blades, activity factor, camber and diameter incorporating blade sweep, tip proplets, advanced composite materials, advanced airfoils, advanced prevision synchrophasing and counter-rotation are presented. The resulting DOC, fuel burned, empty weight and acquisition cost benefits are presented for resizings of the two baseline airplanes.

Six-bladed propellers having advanced composite blades, advanced airfoils, tip proplets and advanced prevision synchrophasers provided the maximum DOC improvements for both airplanes. DOC and fuel burned were reduced by 8.3% and 17.0% respectively for the Convair airplane and by 24.9% and 41.2% respectively for the Lockheed airplane. The larger reductions arose from a baseline definition with very heavy fuselage acoustic treatment. An alternate baseline, with a cabin noise 13dB in excess of the objective, was also studied. DOC and fuel burned improvements were reduced to 6.6% and 14.1% and the cabin noise was reduced to the 82dBA target level.

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SUMMARY

Hamilton Standard completed a study to define the potential benefits of advanced technology propellers for future commuter aircraft. A technology level projected to be available in the post-1955 time period was used for the purposes of propeller definition and start of commercial development. The Small Transport Aircraft Technology (STAT) Propeller Study was made under contract to NASA-Lewis for two airplanes selected from airframe studies sponsored by NASA-Ames. A convair, 30 passenger, 0.47 Mach airplane and a Lockheed, 50 passenger, 0.70 Mach airplane were selected.

The objectives of the STAT propeller study were: (1) to confirm or modify the airframe companies' estimations of propeller performance, noise levels, weight, and cost and the resulting airplane DOC, fuel burned, empty weight and acquisition cost, (2) to evaluate the potential benefits that advanced technology propellers can offer the commuter airlines, (3) to select advanced technology propellers providing the largest DOC benefits for the two selected airplanes, (4) to recommend future research needed in the development and demonstration of the selected advanced technology propellers, and (5) to provide performance data and procedures from which propeller noise levels, weights, costs, maintenance costs, and reliability could be determined. These objectives were Tasks I through V of this study.

The study results showed that significant reductions in DOC, fuel burned, empty weight and acquisition cost are potentially available for both airplanes. These reductions were afforded by improvements in performance, noise levels, weights, and costs of the advanced technology propellers. This study has also shown that the stringent noise requirements established for the STAT airplanes are of major importance in the selection of propellers for the advanced technology airplanes.

Multi-bladed propellers providing the largest DOC benefits were selected for both the Convair and Lockheed airplanes. These single rotation propellers had six lightweight advanced composite blades, advanced airfoil sections, tip proplets and advanced preci sion synchrophasers. The Convair airplane had narrow (70) activity factor, unswept propeller blades, and the Lockheed airplane had thin, wide (175) activity factor propeller blades with 45° of tip sweep. These propellers improved DOC by 8.3% and 24.9%, fuel burned by 17.0% and 41.2%, empty weight by 12.0% and 49.9% and acquisition cost by 2.5% and 12.0% respectively for the Convair and Lockheed baseline airplanes. The larger improvements were primarily afforded by a near elimination of the very heavy acoustic treatment added to the fuselage of the Lockheed baseline airplane. The baseline modification was necessary in order to comply with the 82dBA cabin noise level objective. The weight of acoustic treatment amounted to more than 20% of the empty weight of the Lockheed baseline airplane, but to only about 5% for the Convair baseline airplane. Whereas Lockheed's baseline acoustic treatment amounted to only 4% of the airplane empty weight, the required baseline confirmation analysis showed the cabin noise would be 13 dB in excess of the study objective. Compared to the Lockheed level of baseline acoustic treatment, the selected advanced technology propeller improved DOC by 6.6%, reduced trip fuel by 14.1% and lowered cabin noise by 13 dB.

INTRODUCTION

Earlier airframe and propulsion system studies had been targeted towards the future development of more fuel efficient and economical airplanes. The airframe contracts were managed by NASA-Ames and the propulsion system contracts were managed by NASA-LeRC. Two airplanes which were selected from these studies served as baselines for assessing the potential benefits of advanced technology propellers. The baselines are a 30 passenger, 0.47 cruise Mach number Convair airplane (Ref. 1) and a 50 passenger, 0.70 cruise Mach number Lockheed airplane (Ref. 2).

The propeller selections and the performance, noise level, weight and cost evaluations for the baseline airplanes were made by Convair and Lockheed. The evaluations were reviewed and generally modified as Task I of this study. This effort established consistent reference levels of performance, noise, weight and cost so that the potential benefits of advanced technology propellers to commuter airplanes could be assessed.

The commuter airplane fuel efficiency and economical operation benefits were defined in Task II of this STAT study. These were measured as improvements in airplane direct operating cost (DOC), fuel burned, empty weight and acquisition cost in relation to the Task I baseline values. The improvements include the benefits due both to advanced technology parameters and to improved propeller selection procedures for the resized commuter airplanes. Sensitivity factors provided by NASA-LeRC were used to relate propeller performance, noise levels, weights and costs with benefits for two airplanes having mission stage lengths of 185 kilometers (100 n. miles). Cruise Mach numbers were 0.47 and 0.70 at altitudes of 5180 and 4570 meters (17000 and 15000 feet) for the Convair and Lockheed airplanes respectively.

The propeller parameters studied include diameter, tip speed, camber, width, thickness, number of blades, sweep, tip proplets, counter-rotation, blade materials, advanced airfoils and advanced precision synchrophasers. These were studied individually and in various combinations using a technology level projected to be available in the post-1985 period.

Advanced technology propellers were selected for each resized baseline airplane in Task III. The selections were made from the Task II parametric results, and these are the propellers which provide the maximum potential DOC improvements.

This advanced technology propeller study represents today's methodologies with judgements on the aerodynamics, acoustics, structures, weights, and costs of future propellers for advanced technology commuter airlines. The methodologies, procedures, criteria, etc. that were used are described and/or presented in Appendixes A through E. Recommendations for research to improve the methodologies needed to develop and demonstrate the potential benefits of advanced technology propellers for commuter airplanes of the mid to late 1980's are presented in Task IV.

Two data packs covering a wide range of propeller parameters were prepared in Task V of this study. These were for current and advanced technology propellers applicable to commuter airplanes. The data packs were submitted to NASA-LeRC at earlier dates and were distributed by them to the other STAT contractors. These included propeller performance tabulations, noise level prediction procedures and weight, cost, maintenance and reliability information.

The STAT programs involved advanced and innovative airframe, propeller and engine concepts for commuter airline usage. The noise level requirements for these studies were considerably more severe than for existing aircraft. The requirements were: (1) an overall sound pressure level of 85 dB in the cabin and, (2) noise levels in the far-field specified by FAR 36, Amendment 8, Stage III, minus 8 EPNdB. Parametric trades were made which optimally balanced propeller performance, weight and cost with the fuselage acoustic treatment weight and tip speed necessary to meet the cabin and far-field noise level requirements. Airplane DOC was used as the measure of optimality. These noise level requirements had a large influence on the advanced technology parameters that most improved DOC and fuel burned.

PROGRAM DESCRIPTION

Hamilton Standard was contracted by NASA-Lewis to conduct a propeller study for Small Transport Aircraft Technology (STAT). The purpose of the contract was to identify and evaluate a set of candidate advanced propeller and Prop-Fan technologies that can be exploited to overcome deficiencies or enhance the performance and economics of current technology commuter aircraft.

The scope of this study was covered by Tasks I - V for the STAT Propeller Study as follows:

Task I. Select from the NASA-Ames sponsored airframe studies a baseline commuter airplane for the following aircraft categories:

Aircraft Category	Passengers	Minimum Cruise Speed	Approx. Engine Power (2 Engine Aircraft)
1	30	129 m/s (250 KIAS)	1119 kw (1500 hp)
3	50	Mach 0.6 - 0.7	4474 kw (6000 hp)

Confirm the airframers' performance, noise level, weight and cost evaluation for the baseline propeller selections.

Task II. Identify and evaluate a set of candidate propeller and Prop-Fan technologies that can be exploited to overcome deficiencies or enhance the performance and economics of current technology commuter aircraft.

Task III. Make a trade-off analysis of major propeller design parameters utilizing the information generated in Task II to define an advanced technology design for each airplane.

Task IV. Prepare and submit Hamilton Standard's views as to the content of a government sponsored research program that would best aid in development and demonstration of those advanced propeller technologies and design concepts found to be beneficial in this study.

Task V. Generate parametric propeller data packages for commuter aircraft applicable to current and advanced technology propellers. These data shall include aerodynamic performance, acoustic performance, weight, costs, maintenance, and reliability.

The study results for Tasks I through IV and a description of the content of the Task V parametric data packs are presented in the remaining sections of this report.

RESULTS AND DISCUSSION OF RESULTS

The STAT advanced technology propeller study for commuter airplanes was divided into the five tasks described in the previous section. Although these tasks are interrelated, the requirements were distinct. Therefore, the results and the discussion of the results are presented in individual sections allocated for each task.

Task I - Baseline Propeller and Airplane Confirmation

Introduction

The two baseline airplanes that were selected from the airframe company STAT contracts and the propellers that were selected by the airframers are illustrated in Figures 1 and 2. Performance, noise levels, weight and cost evaluations for these baseline propellers were obtained from the airframe companies. It was important to compare these quantities with those predicted by the methodology used in this study. Where differences were found, the airframers evaluations were modified and new baselines for assessing the benefits of advanced technology propellers were established.

Convair's baseline propeller selection and performance predictions were made from the Hamilton Standard "Generalized Method of Propeller Performance Estimation," PDB6101A, referred to as the Redbook. Although the propellers typified by the performance levels in the Redbook are representative for many current commuter airplanes, most were defined to have less efficient propellers with round shanks and poorer blade/spinner junctures. Convair's baseline propeller and performance estimations were modified to reflect the less efficient configuration on the basis of increased profile and interference drags described by Hoerner (Ref. 3). The progression of propeller technology from round shank blades in use in the 1940-1980 era through the 1990-type advanced propellers used in this study are depicted in Figure 3. Although this study utilized the poorer baseline propeller, the airplane benefits for the selected advanced technology propeller are presented relative to both baseline propellers in the Task III discussions.

Lockheed's baseline propeller selection, on the otherhand, was considered to be representative for current high speed turboprop aircraft. The 0.70 Mach cruise condition of the airplane requires thin airfoils at all blade radii. Lockheed, in defining baseline performance levels and in executing their STAT airplane study, utilized a performance data pack provided by Hamilton Standard for the Electra propeller.

Confirmation Analysis

The results of the analyses to confirm and/or modify the performance, noise level, weight, and cost estimations for the baseline propellers are shown in Tables 1 and 2. The modifications necessary for the two baseline airplanes are identified in the tables as the Hamilton Standard evaluations.

The performance differences in Table 1 were mainly due to the round shank propeller technology base selected for the Convair airplane. The smaller differences in Table 2 appear to reflect interpolation errors in the use of the performance data provided to Lockheed.

Tables 1 and 2 show large differences between the airframe company and Hamilton Standard far-field and cabin noise level predictions. The Hamilton Standard predictions show neither baseline airplane met the required FAR 36, Amendment 8, Stage III minus 8 EPNdB far-field noise levels and that Convair overestimated the cabin noise level by 7.5 dB while Lockheed underestimated the level by 13 dB. Because of the cabin noise level estimation differences the acoustic treatment material required to meet the 85 dB interior noise level objective was also changed, as shown in Tables 1 and 2.

Acoustic treatment weight estimations were obtained from the curves in Figure 4 Variations in the treatment weight necessary to reduce the cabin overall sound pressure level to 85 dB are plotted against the required noise attenuation. These curves were derived from the Convair and Lockheed baseline weight/attenuation analyses and from a mass scaling expressed by: $W_T = (10^{\Delta dB/20} - 1)Wo$. W_T is the acoustic treatment weight, Wo is the reference sidewall mass and ΔdB is the noise attenuation required to meet the 85 dB cabin noise level. Using Convair's and Lockheed's attenuation weight predictions and the procedure explained in Appendix A, Wo is 117 kilograms (258 lbm) and 98 kilograms (216 lbm) respectively. The treatment weight variations shown in Figure 4 were also used in the Task II and Task III advanced technology propeller investigations.

Changes to the baseline propeller performance, noise level, weight and cost, the governing sensitivity factors and the resulting DOC, fuel burned, empty weight and acquisition cost changes for the two baseline airplanes are shown in Tables 3 and 4. DOC, fuel burned, etc. are shown to be reduced by from 5% to 12% as a result of the confirmation analysis for the Convair airplane, but increased by from 13% to 38% for the Lockheed airplane. These redefined levels were used as the new baselines to assess the potential benefits of advanced technology propeller parameters.

DOC and fuel burned improvements for the Convair airplane were primarily due to reductions in acoustic treatment weight and propeller cost. These were partially offset by the poorer efficiency of the round shank baseline propellers. For the high speed airplane these factors were predominately influenced by 2677 kg (5900 lbm) of fuselage acoustic treatment added to the treatment already incorporated by Lockheed. The resulting treatment weights amounted to nearly 20% of the empty weight of the Lockheed airplane and to only about 5% for the Convair airplane. Although the parametric study, Task II, and the advanced technology propeller selection, Task III, were based upon the revised baselines, DOC and fuel burned benefits are reported in Task III relative to both the Hamilton Standard and the Lockheed defined acoustic treatment definitions.

Task II - Parametric Study of Advanced Technology Propellers for Commuter Airplanes

Introduction

Potential benefits in DOC, fuel burned, empty weight and acquisition cost due to advancements in propeller technology were calculated for both the Convair and Lockheed commuter airplanes. The study included a large number of propeller and Prop-Fan configurations with both current and advanced technology propeller parameters. The Hamilton Standard Prop-Fan is a multi-bladed, highly loaded, and variable pitch propeller which has thin, and typically swept blades which are designed for high airspeed application. Benefits to commuter airplanes provided by changes in efficiency, noise level, weight and cost were calculated for advanced technology propellers incorporating variations in:

1. Number of blades
2. Activity factor
3. Camber
4. Thickness ratio

5. Diameter

6. Blade material

7. Airfoil shape

8. Blade sweep

9. Blade tip proplets

10. Counter-rotation

11. Advanced precision synchrophasers

In addtion to these parameters, the inboard airfoil shapes and blade root/spinner junctures of each propeller were improved in relation to the baseline propellers for the Convair airplane. These improvements were included in the propeller analysis (described in Appendix B) and increased efficiency for the mission of the low speed airplane by about 2 1/2%. The analysis included the blade element drag and lift coefficient improvements for the thinner airfoils and reductions in the boundary layer interference losses (3) at the blade root/spinner junctures. Some of the advanced technology propeller concepts that were either included or considered for this study are illustrated in Figure 5.

In performing this task it became apparent that the very stringent STAT propeller noise level requirements (85 dB OASPL in the cabin and FAR 36, Amendment 8, Stage III minus 8 dB in the far-field) would have a dominating influence on the study results. In fact, the noise requirements had a larger influence on the airplane benefits than either the performance, weight or cost of the propellers. Since noise levels are strongly influenced by propeller tip speed, this became one of the principal study variables. The cruise/take-off tip speed relationships that were established for the baseline propellers by the airframers were also used for the advanced technology propellers. That is, a constant speed was selected for the mission of the high speed airplane, while cruise tip speed was allowed to vary between 80% and 100% of the take-off speed for the low speed airplane. A speed ratio was selected for each propeller configuration that produced the largest DOC improvement for the low speed airplane.

The revised baseline values of propeller performance, noise level, weight and cost and airplane DOC, fuel burned, empty weight, and acquisition cost for both baseline airplanes are summarized in Table 5. These quantities, established in the Task I confirmation and modification study, were used as the references to establish the potential benefits of advanced technology propellers for the STAT commuter airplanes.

Two operating conditions for each airplane were selected to represent the 100 nautical mile missions. These were an end of take-off and a cruise condition for the Convair airplane, and a start of climb and a cruise condition for the Lockheed airplane. The operating conditions and the equations used to define mission weighted performance improvements for each airplane are shown in Table 5. The equations approximate fuel burned average performance levels for the two chosen conditions.

The amount that the baseline propellers exceed the far-field noise requirements are referred to as exceedances, and are shown in Table 5. The individual exceedances at both the take-off and sideline measurement points as well as the sum of these exceedances are shown. Approach noise levels are not included as they were previously shown to be below the required noise level requirements (Tables 1 and 2). Acoustic trade-off guidelines which have been established by the FAA were used to assure that each candidate propeller configuration would meet the take-off flyover and sideline measurement point requirements. The FAA guidelines state that:

- Noise may be exceeded at one or two measuring points, provided that:
  - The sum of the exceedances are not greater than 3EPNdB
  - No single exceedance is greater than 2EPNdB
  - The exceedances are offset by reductions at other measurement points

It was evident that the advanced technology propellers must generate substantially less noise than the baseline propellers. This, in spite of the allowable noise trade-offs, was necessary to meet the far-field noise requirements. Far-field noise levels were calculated for each propeller configuration and for a range of tip speeds. From these, the maximum allowable tip speeds to meet the traded noise requirements were defined. The tip speeds, as will be discussed later, were generally lower than those selected by Convair and Lockheed for their baseline propellers.

Resized Airplane Sensitivity Factors

The sensitivity factors which relate improvements in propeller performance, noise level, weight and cost to benefits in resized airplane performance and economy are shown in Table 6. These were provided by NASA-Lewis and are the same sensitivity factors used in the Task I confirmation analyses for the baseline airplanes. Each sensitivity is a partial derivative expressing the amount of airplane benefit (in terms of DOC, fuel burned, empty weight or acquisition cost) due to changes in propeller performance, noise level (in terms of acoustic treatment weight), weight and cost. For example, the 0.56 DOC sensitivity to mission weighted efficiency, shown in Table 6, is $\partial \Delta DOC / \partial \Delta \bar{\eta}$, and states that DOC improves 0.56% for a 1% improvement in mission weighted efficiency. If AB is used to denote an aircraft benefit, such as DOC, the total change in AB is expressed as:

$$\Delta AB = \Delta\bar{\eta} \frac{\partial AB}{\partial \Delta\bar{\eta}} + \sum \frac{\Delta WGT}{45.4} \frac{\partial AB}{\partial WGT} + \sum \frac{\Delta cost}{10000} \frac{\partial AB}{\partial \Delta cost}$$

The signs of the propeller changes in Table 6 were selected so that all propeller improvements (higher efficiency, lower near field noise and lower weight and costs) produced a positive (improved) airplane benefit. An example which illustrates the use of the sensitivity factors is shown below. The propeller changes were assumed for this example and the DOC sensitivity factors are from Table 6 for the Convair airplane:

Propeller Parameter Changes:

$\Delta\bar{\eta}$	(Mission Avg.)	=	+4.0% (Effic. increase)
ΔWGT	(2 Props)	=	-45.4 kg (-100#) (Wgt. increase)
ΔWGT	(Acous. Treat)	=	+317.5 kg (+700#) (Wgt. decrease)
ΔCOST	(2 Props)	=	-$15,000 (Cost increase)
ΔCOST	(Prec. Sync)	=	-$5,000 (Cost increase)

$$\Delta DOC = \Delta\bar{\eta} \frac{\partial DOC}{\partial \Delta\bar{\eta}} + \frac{\Sigma \Delta WGT}{45.4} \frac{\partial \Delta DOC}{\partial \Delta WGT} + \frac{\Sigma \Delta cost}{10000} \frac{\partial \Delta DOC}{\partial \Delta cost}$$

$$\Delta DOC = 4.0\ (0.56) + 6.0\ (0.37) - 2.0\ (0.18)$$

$$\Delta DOC = +\ 4.10\%\ \text{(Improvement)}$$

Advanced Technology Propeller Parametric Trends

The major objective in Task II was to form parametric data bases from which maximum DOC improvements for each airplane could be defined. These data bases were formed from propeller performance, noise level, weight and cost predictions and from the sensitivity factors, and they also include changes in fuel burned, empty weight and acquisition cost. Some of the parameter effects (i.e., number of blades, total activity factor, proplets, etc) on propeller performance, noise, weight and cost are presented. Some illustrations of the effects that these parameters had on DOC and fuel burned are also presented.

Propeller Noise Levels: The near-field and far-field noise level methods used to establish noise level trends for this study are discussed in Appendix A. The methods are based upon measured and calculated noise generalizations which do not recognize blade element loading variations. The methods, therefore, do not account for noise level differences due to changes in camber, activity factor, airfoil shape or tip proplets. Blade material is assumed to have no effect on noise and synchrophasing benefits only occur in the near field noise prediction.

The importance of the far-field and the cabin noise levels to the efficient and economic operation of the STAT commuter airplanes has already been emphasized. The major impacts of the noise requirements on the propellers and on the study were that far-field propeller noise needed to be reduced through careful propeller parameter and tip speed selection and, where necessary, acoustic treatment material was added to the fuselage sidewalls.

Variations in propeller far-field noise with take-off tip speed and number of blades are shown in Figures 6 and 7. The noise level variations represent samples of changes in exceedance levels (propeller noise minus required noise) for the two airplanes. The individual levels at the take-off and sideline acoustic measuring points and the sums of these exceedances for the Convair airplane are shown in Figures 6a, 6b and 6c. These are for 4, 6 and 8 bladed, single rotation, unswept, 3.5 m (11.5 ft.) diameter propellers, and are for any level of total activity factor. The FAA traded noise level guidelines are indicated by the three lines labelled "allowable" on the figure. The maximum allowable tip speeds are the lesser of these governed by the three guidelines. The limiting tip speeds were 225, 227 and 250 meter per second (740, 745 and 820 feet per second) for the 4, 6 and 8 bladed propellers respectively. These limits were governed both by the individual condition exceedances and by the exceedance sums. The approach condition noise levels were low for each propeller configuration investigated, and the third FAA guideline provision is therefore satisfied. The far-field noise exceedances for the 3-bladed baseline propeller are also shown. The irregular noise trend with number of blades at the take-off condition was caused by ground reflections for a 1.22 meter (4 foot) high microphone over grass covered dirt. These effects produce noise level fluctuations varying with blade passage frequency that amount to as much as ± 2.5 dB.

Noise exceedance levels for the Lockheed airplane are shown for 6 and 8 bladed single rotation propellers in Figure 7. For simplicity, only the exceedance sums are shown, and these are for propellers having a 3.66 m (12.0 ft) diameter, any total activity factor, unswept blades in Figure 7A and 45° swept blades in Figure 7B. The maximum allowable tip speeds at both the take-off and sideline conditions are noted by the symbols on the curves. The take-off condition is shown to be the most restrictive of the far-field noise requirements and the allowable tip speeds were 177 and 174 m/s (582 and 573 ft/sec) respectively for the unswept 6 and 8 bladed propellers and 190 and 189 m/s (623 and 621 ft/sec) respectively for 45° swept, 6 and 8 bladed propellers. Approach oondition noise levels were low and offset the take-off and sideline noise exceedances.

Maximum allowable take-off tip speeds were similarly defined for each of the investigated propeller configurations. These limits are summarized in Table 7 for both the Convair and Lockheed airplanes.

Cabin noise level predictions were also made for the many propeller configurations in this parametric study. These were essential so that the weights of acoustic treatment material necessary to meet the required cabin noise level (85 dB overall) could be defined. The cabin noise level predictions are influenced by number of blades, tip diameter, blade tip to fuselage clearance, sweep, synchrophasing and operating condition. Appendix A, which discusses the mechanisms by which each parameter affects noise, explains that no cabin noise level decrease was attributed to blade tip proplets and that no increase was attributed to dual counter-rotation propellers. Recent Hamilton Standard tests, discussed in Appendix A, have indicated that overall sound pressure level reductions of 8 dB can be expected with precision synchrophasing. This amount of reduction was included in the propeller parametric studies for both airplanes.

Two examples of cabin noise level reductions relative to the Convair and Lockheed baseline propellers are shown in Figures 8 and 9. Both show variations with cruise tip speed and number of blades, while the effect of blade tip sweep for the high speed Lockheed airplane is shown in Figure 9. In all cases the cabin noise levels are reduced with decreasing tip speed and increasing number of blades. The noise reductions are for the propeller configurations indicated on the figures, but they do not include the eight decibel reduction attributed to advanced precision synchrophasing.

The example cabin noise level reduction curves for the Convair airplane are tic marked to show the far-field noise limiting tip speeds for the range of cruise to take-off tip speed ratios studied. Larger cabin noise level reductions were achievable at the lower cruise-to-take-off tip speed ratio. However, none of the tic marked reductions are sufficient to reduce the untreated cabin noise level from the 97.5 dB baseline level to the required 85 dB. Therefore, each of the indicated points in Figure 8 would require the addition of acoustic treatment by the amounts defined in Figure 4. The inclusion of 8 dB for advanced precision synchrophasing permitted a near elimination of the acoustic treatment material with 6 and 8 bladed propellers at either cruise-to-take-off tip speed ratio.

The examples in Figure 9 show that 45° of blade tip sweep reduces cabin noise in the Lockheed baseline airplane by from 4 to 7 decibels, but that from 16 to 24 decibels attenuation are still required to achieve the required 85 dB at the far-field noise limiting tip speeds. Although advanced precision synchrophasers lowered the attenuation requirements by 8 dB, some acoustic treatment material was required with each of these propellers for the Lockheed airplane.

Operation at tip speeds lower than the far-field noise limits were also examined. Although the acoustic treatment weights were generally reduced, DOC was not improved at the lower tip speeds. Propeller performance, weight and cost changes more than offset the lower acoustic treatment weights at the reduced speeds.

The noise attenuation levels required for each propeller configuration accountable in the analysis are shown in Table 8. These attenuations were accomplished by adding fuselage acoustic treatment and/or advanced precision synchrophasing. Advanced synchrophasing reduced attenuation requirements by 8 dB, resulting in reduced acoustic treatment weights as derived from Figure 4.

Propeller Performance: Examples of performance improvements relative to the baseline propellers are shown in Figures 10 through 22. These examples are for both current and advanced technology propeller parameters selected from the many configurations included in the airplane benefit analysis. Relatively large performance improvements are indicated in some cases, and these are due not only to each principal propeller parameter but also to the other parameter changes indicated on the figures. Figure 16, which shows the effect of total activity factor (TAF) and tip speed on mission weighted performance improvements, illustrates this point. Here the efficiency improvement variations with TAF are illustrated by the differences between the four individual curves. The absolute level of performance improvement for the 300 TAF curve, which is the same total activity factor as the Convair baseline propeller, includes the effects of: improved blade roots, optimum camber selection and design, advanced airfoils and an increase from 3 to 6 blades. Each of the other TAF curves also include the benefits of these propeller parameters.

Figures are presented in pairs to show examples of propeller parameter effects on performance for each airplane. The far-field noise limiting tip speeds are indicated on each figure. In some instances these limits prohibited achieving the maximum performance improvements.

The methodologies and procedures that were used to define the propeller performance are described in Appendix B. Whereas this does not present a comprehensive description, the origins for the performance assessments for each propeller parameter are indicated.

Not only were the propeller parameters that were listed earlier included in this study, but each propeller also incorporated improvements in the aerodynamic design selections of blade twist, camber, width and thickness distribution. Furthermore, some of the parameters that would normally be classified as current technology actually represent advancements in propeller state-of-the-art design. For example, current propeller design guidelines limit minimum blade widths such that blade activity factors must be greater than about 90. This limit was lowered to 70, and potentially represents acceptability for the narrow propeller blades required for the 0.47 cruise Mach number advanced commuter airplane. Activity factors less than 70 were also included in the parametric study, but only to assess the effects of the blade width design limit on the airplane. The 70 AF blade design limit was not found to be critical for the Lockheed airplane since its higher cruise Mach number and higher propeller loadings precluded the need for advanced low activity factor blades. In some instances, however, it was necessary to increase the propeller blade thickness ratios for both airplanes. Increased thickness to chord ratios were necessary for the Convair airplane to assure practical designs for propellers with activity factors below 105. The Lockheed airplane, on the other hand, does not require blades that are as narrow, but the airfoils must be very thin for these propellers to produce high efficiency levels at the 0.70 Mach cruise condition. For this study it was projected that the desired thickness ratios here-to-fore associated with Hamilton Standard's 0.80 design Mach number Prop-Fans could be accommodated for propeller blade activity factors as low as 175. Activity factors as low as 100 (TAF = 800, B = 8) were included in the study of the Lockheed airplane. The propeller blade thickness ratios were increased proportionately as activity factor was lowered from 175 to 100. The thicker blades not only detract from the performance levels but also increase propeller weight and cost. Each detrimental effect of the thick blade was incorporated into the parametric studies and in some instances inhibit the benefits that would otherwise be possible. Where practical, these instances are noted in the following discussions of each propeller parameter.

Camber - An example of the variations in performance with propeller integrated camber levels and with tip speed are shown in Figures 10 and 11. Performance trends are shown for the two operating conditions selected to represent the missions of each airplane. Both figures show that low camber produces the highest efficiency levels at cruise, but that high camber is required to maximize take-off and climb performance. Camber levels which produce the largest improvements in mission weighted performance were selected from similar information calculated for each STAT propeller configuration. Variations in the optimum camber levels and the resulting maximum mission weighted performance improvements are illustrated in Figures 12 and 13 as a function of take-off tip speed. These were derived from the preceding two figures for the low and high speed airplanes respectively. Figures 12A and 12B show the camber and performance variations at cruise to take-off tip speed ratios equal to 1.0 and 0.8 for the Convair low speed airplane. In this example the constant speed propeller produces the highest performance levels at tip speeds at least up to the far-field noise limits. The maximum performance and optimum camber level variations shown in Figure 13 are for the Lockheed airplane constant speed propellers.

Number of Blades - The effects of blade number and take-off tip speed on mission weighted performance improvements are shown in Figure 14 for the Convair airplane and in Figure 15 for the Lockheed airplane. The blade activity factors are only 70 and 52.5 respectively for the 6 and 8 bladed, 420 total activity factor propellers in Figure

14 and they are only 150 for the 8 bladed propellers for the high speed airplane in Figure 15. These relatively narrow propeller blades were thickened to be structurally feasible, and the usual performance improvements for increasing number of blades was not as evident as with thin blades.

Performance trends at speed ratios of 1.0 and 0.8 are shown in Figure 14 for the Convair airplane. At the far-field noise limiting tip speeds, the constant speed ratio produced the larger performance improvements for the 4 and 6 bladed propellers. An 0.80 speed ratio was calculated to be slightly better for 8 bladed propellers. The improvement was about the same as with 6 blades at the lower speed ratio. Figure 15 shows that the performance improvements for the Lockheed airplane at the limiting tip speeds were the same for the 6 and 8 bladed propellers. These propellers had 45° of aft blade tip sweep and produced mission weighted efficiencies nearly 4% higher than the baseline propeller.

The performance and noise trends that have been presented thus far indicate that the selections of optimum propeller configurations and appropriate tip speeds were rather complex tasks. The selections were simplified later as the combined effects of performance, noise, weight and cost were summed into the associated DOC benefits. Some of the selection difficulty can be seen and sorted out from the information which has already been presented. This is illustrated in the table below:

NO. BLADES & SPEED RATIO EFFECT OF PERFORMANCE & CABIN NOISE IMPROVEMENTS FOR CONVAIR 30 PAX AIRPLANE DIAM = 3.5m (11.5') TAF = 420

		Cruise/Take-Off Tip Speed = 1.0			Cruise/Take-Off Tip Speed = 0.80		
			Treatment Weight			Treatment Weight	
No. Blades	Take-Off Tip Speed	$\Delta\bar{\eta}$	W/O Prec. Sync.	With Prec. Sync.	$\Delta\bar{\eta}$	W/O Prec. Sync.	With Prec. Sync.
	m/s (fps)	%	kg (lb)	kg (lb)	%	kg (lb)	kg (lb)
4	226 (740)	6.3	268 (590)	36 (80)	4.7	154 (340)	0 (0)
6	227 (745)	6.8	200 (440)	11 (25)	5.5	86 (190)	0 (0)
8	250 (820)	6.3	181 (400)	0 (0)	6.7	64 (140)	0 (0)

The tabulated numbers were taken from Figures 4, 8 and 11 and, where indicated, incorporate the 8 dB cabin noise reductions attributed to advanced precision synchrophasing. Based upon performance and treatment weight it is evident that the best configuration without advanced precision synchrophasing was the 8 bladed propeller operating at an 0.80 speed ratio. With advanced synchrophasing the 6 bladed constant speed propeller and the 8 bladed propeller at a tip speed ratio of 0.80 appear to be very nearly equivalent.

The sensitivity factors, Table 6, help in the trading process and they show that a 1% efficiency improvement and a 68 kilogram (150 pound) reduction in acoustic treatment provided equal DOC benefits. In looking at the total picture, which is presented later, the weight and cost of the propellers must also be included in the airplane benefit analyses. These analyses indicated that a tip speed ratio near 1.0 generally produced the largest DOC benefits for the Convair airplane. The subsequent performance trends for both airplanes are presented for constant propeller speed operation.

Total Activity Factor - The effects of total activity factor on mission weighted performance improvements relative to the Convair and Lockheed baseline propellers are shown in Figures 16 and 17. These figures include the far-field noise limiting tip speeds and show the total activity factors which yielded and largest performance improvements. These total activity factors were approximately 540 for the Convair and 1200 for the Lockheed airplane. In selecting optimum configurations, however, it was necessary to account for the increased weight and cost that resulted from increased total activity factor propellers. The configurations which produced the maximum DOC benefits did consider weight and cost, as well as noise levels, and the optimum TAF's were found to be lower than those based only on performance considerations.

The performance levels at total activity factors of 300, 420, and 540 in Figure 16 and 800 in Figure 17 were adversely influenced by the blade thickening that would be required for the structure of these narrow bladed propellers.

Diameter - The effects of propeller diameter on mission weighted performance are shown in Figures 18 and 19. The baseline propeller diameter for the Convair airplane is 3.5 meters (11.5 feet), and Figure 18 shows performance variations for both larger and smaller propeller diameters. The performance improvements relative to the baseline propeller include not only the diameter effect but also the number of blades, higher total activity factor and other effects that were discussed earlier. The effect of diameter as an individual variable can be obtained from the relative level of the performance improvements that are shown.

At all tip speeds, the largest diameter provided performance improvements for the Convair airplane, and it also permitted the highest far-field noise limiting tip speed. At the limiting tip speeds, the efficiency improvements were 4.2%, 6.2%, and 8.0% for the 3.2, 3.5, and 3.8 meter (10.5, 11.5, and 12.5 foot) diameter propellers respectively.

Similar diameter effects on mission weighted performance improvements and limiting tip speeds are shown in Figure 19 for the Lockheed airplane. At the limiting speeds, the performance improvements in relation to the baseline propeller were 1.7% and 4.0% respectively for the 3.35 and 3.65 meter (11.0 and 12.0 foot) diameter propellers.

Proplets - The effect of blade tip proplets on mission weighted performance improvements for both airplanes are shown in Figure 20. These improvements are relative to the same propellers without proplets, rather than to the baseline propellers as was the case in the previous examples. The performance increments are for 6 bladed propellers and incorporate the same total activity factors as previously shown in Figures 16 and 17. Those figures indicated that the largest performance improvements were achieved with total activity factors of 540 and 1200 for the Convair and Lockheed airplanes respectively. Figure 20 shows that mission weighted performance can be potentially improved an additional 1.30% and 1.15% by adding proplets to those two propellers.

Performance improvements for propellers with proplets were based upon Spillman's experimental results for wings with wing tip sails (Ref. 4). These improvements have been confirmed by the theoretical work of Sullivan (Ref. 5). The propeller performance methods, including the effects of proplets, are described in Appendix B.

Counter-Rotation - The benefits of counter-rotation on mission weighted propeller performance are shown in Figure 21 for the Convair airplane and in Figure 22 for the Lockheed airplane. The potential efficiency increments due to counter-rotation are shown in Figures 21(A) and 22 (A), and they represent improvements relative to single rotation propellers having the same number of blades. These show that the potential efficiency improvements are largest at low tip speeds where the thrust lost to unrecovered swirl in the single rotation propeller slipstream is largest. Figures 21 (B) and 22 (B) show the efficiency improvements relative to the baseline propellers for the two counter-rotation configurations indicated on the figures. Although these show that large efficiency increments were possible, the low tip speeds required to meet the far-field noise requirement with counter-rotation propellers limited the improvements to 7.7% for the low speed airplane and to only 1.7% for the high speed airplane. The limiting tip speed was so low for the Lockheed airplane that an excessively high, 1840 total activity propeller was required to meet the take-off performance requirement. This propeller was not very effective in improving performance at the climb and cruise conditions.

Sweep - The effects of 45° of aft blade tip sweep on mission weighted performance improvements are shown for both airplanes in Figure 23. As with proplets, the performance improvements shown are relative to the same propellers without sweep. Mission weighted performance improvements varied from 0.6% to 1.8% for the high speed airplane at tip speeds from 152 meters per second (500 feet per second) to 244 meters per second (800 feet per second). At the tip speed to meet the far-field noise requirement the improvement is limited to approximately 1%. These are mission weighted performance improvements and for the Lockheed airplane they were averaged for an 0.70 Mach cruise and an 0.40 Mach climb condition, as shown earlier in Table 5. The effect of sweep at the cruise condition alone is approximately twice the improvements shown in the figure.

For the low speed airplane the propeller relative Mach numbers were subcritical and, as a result, performance levels were unaffected by blade sweep. The incorporation of sweep, as shown in Table 7, did permit the required far-field noise levels to be met at higher tip speeds. The higher tip speeds were generally beneficial to propeller efficiency levels for both airplanes.

Propeller Weight and Cost - Propeller weights and cost are important in that they also affect airplane fuel efficiency and economy. Their effects on DOC, fuel burned, empty weight and acquisition cost were included in this advanced technology propeller parametric study.

The weight and cost of each propeller configuration was based upon empirical equations for current technology parameters and upon factors which correct weight and cost for the advanced technology parameters. A few of the propeller weight and cost trends are shown in Figures 24 through 30. These were derived from the weight and cost equations and correction factors shown in Appendixes C and D.

The two major aircraft categories, typified by the low speed airplane and the high speed airplane, provided the two distinct propeller weight and cost categories used in this study. The propeller weights and costs include blades, hub, pitch control and spinner for double acting propeller systems.

Variations in 6-bladed propeller weights and costs are shown in Figures 24 and 25 for the Convair airplane and in Figures 26 and 27 for the Lockheed airplane. These are for two propellers per airplane and are based upon the equations in Appendixes C and D. The weights and costs which are shown are absolute values for the specific propeller geometries indicated on the figures.

The effects of the number of blades on propeller weight and cost are shown in Figures 28 and 29 for the low and high speed airplanes respectively. These are approximate corrections to the 6-bladed weights and costs in Figures 24 - 27 and are shown solely to illustrate the number-of-blades effects. The actual weights and costs for this study were derived directly from the equations in Appendixes C and D. Similarly, corrections which account for the effects of diameter on weights and costs for both airplanes are shown in Figure 30. The effects of sweep, proplets, material, etc. on propeller weights and costs can be obtained directly with the weight and cost factors in the appendixes.

Airplane Benefits Derived from Propeller Parameters

The propeller parametric trends discussed in the preceding paragraphs were incorporated into DOC, fuel burned, empty weight, and acquisition cost benefit analyses for the two commuter airplanes. The groundrules for the analyses were: (1) use the baseline airplanes as modified and resized in Task I, (2) meet the FAR 36 Amendment 8, Stage III minus 8 far-field noise requirements, (3) meet the required 85 dB overall sound pressure level in the cabins, (4) meet or exceed the take-off performance of the baseline propellers, and (5) hold payload, range and airspeed constant. The benefit analyses made use of the resized airplane sensitivity factors which were derived for a constant payload, range, and airspeed. Within the framework of these groundrules, the major objective was to define the propeller parameters which provide the largest potential DOC improvements for the Convair and the Lockheed airplanes.

Propeller Configurations: The maximum DOC benefits and the associated propeller geometries were identified through the analysis of a large number of cases. These are summarized in Tables 9 and 10 for the Convair and Lockheed airplanes. For each case the blade number and total activity factor were varied as the advanced technology parameters were evaluated. For example, Case 7 in Table 9 shows the analysis results for 4, 6 and 8-bladed, 11.5 foot diameter propellers with total activity factors that range from 300 to 660. Each of these was a single rotation, unswept propeller with proplets incorporating advanced precision synchrophasers and advanced composite blades. These, and all of the other propellers in Table 9, had improved root airfoils and blade-to-spinner junctures relative to the baseline propellers for this airplane. In addition, the propellers in both Table 9 and 10 incorporated advanced airfoil shapes, improved aerodynamic design and the type of optimum camber selections discussed previously and illustrated in Figures 10 through 13.

The maximum allowable take-off tip speeds which met the far-field noise requirements were used for each of the cases in Tables 9 and 10. Lower tip speeds were also analyzed but did not improve DOC. The cruise tip speeds for the low speed airplane were selected in the 0.80 to 1.00 cruise/take-off tip speed ratio range to provide the largest DOC benefits for each configuration. Tip speeds were fixed for the constant speed propellers on the high speed airplane.

The maximum DOC benefits and the propeller configurations (number of blades and total activity factor) that provided the benefits are shown for each case in Tables 9 and 10. The corresponding fuel burned, empty weight and acquisition cost improvements and the changes in propeller mission weighted performance, weight (including acoustic treatment) and cost (including advanced precision synchrophasers) are also shown.

Six-bladed propellers generally provided larger DOC improvements than either four or eight bladed propellers. Two exceptions, having eight blades, were counter-rotation propellers, Case 10 in Table 9, and single rotation propellers without advanced synchrophasing, Cases 1 and 3 in Tables 9 and 10. Benefits are summarized for both six and eight-bladed propellers for those cases and were used to establish the incremental benefits discussed below. A few cases, noted in Table 9, were constrained by the 70 activity factor blade structural design limit. As shown, this constraint had only a small effect upon the aircraft benefits.

Incremental Benefits: The results of the analyses for the large number of configurations in Tables 9 and 10 provided the data bases from which the incremental benefits in DOC, fuel burned, empty weight and acquisition cost due to many of the individual propeller parameters were derived. These derivations were the culmination of the

Task II effort, and the individual benefits were the foundation for making the two commuter airplane propeller selections in Task III. The benefits for the individual parameters are shown in Table 11 for the Convair low speed airplane and in Table 12 for the Lockheed high speed airplane.

The incremental benefits are simple to use and show percent improvements compared to the Task I modified baseline airplanes. For example, Table 3 showed a DOC of 6.44 cents per seat kilometer (11.93 ¢/sm) for the modified Convair baseline airplane. Table 11 shows DOC is improved 1.4%, decrease DOC to 6.18 cents per seat 2.7% by increasing the number of blades from three to six. These two propeller changes alone, which sum to a DOC improvement of 4.1%, decrease DOC to 6.18 cents per seat kilometer (11.44 ¢/sm). This example not only illustrates the utilization of the tables but also demonstrates that the total benefits can be obtained from superposition of the incremental benefits for each individual propeller parameter.

The validity of superposition of the incremental benefits was verified by the calculated results for the large number of cases investigated. For example, Table 11 shows a 2.3% DOC improvement for the sum of the incremental benefits due to advanced composite blades (0.5%), advanced precision synchrophasers (1.0%) and tip proplets (0.8%). Both the individual and the aggregate benefits are demonstrated by the appropriate pairs of cases in Table 9. Cases 2 and 4, 1 and 2 and 5 and 6 show the individual benefits, listed in the same order as above, while Cases 1 and 7 demonstrate the 2.3% aggregate benefit for the three propeller parameters. In some instances the validity of super-position was not as obvious. For example, Tables 9 and 10 show that 8-bladed propellers are optimum for both airplanes when advanced precision synchrophasers are excluded. However, it was evident that advanced technology propellers would incorporate advanced synchrophasing and that 6-bladed propellers provided the largest benefits. Therefore, the incremental benefits for advanced precision synchrophasers were based upon the 6-bladed propeller cases in Tables 9 and 10.

The incremental benefit derivation for some of the individual parameters was more complex for the high speed than for the low speed airplane. The complexity proved to be more a bookkeeping problem than a benefit summation problem. For example, the individual benefits due to sweep and advanced precision synchrophasing shown in Table 10, were dependent upon the order in which the benefits were assessed. That is, Cases 1 and 2 show advanced precision synchrophasers improve DOC by 5.3% when added to an unswept propeller, while Cases 3 and 4 show the improvement to be only 3.7% when added to a propeller with 45° of sweep. Furthermore, Cases 5 and 6 show that adding 45° of sweep to the synchrophased propeller only improves DOC by 1.6%, while the sweep improvement, from Cases 1 and 3, is 3.2% for propellers which do not have advanced precision synchrophasing. The 6.9% DOC improvement for sweep and advanced precision synchrophasing was obtained by appropriately combining the individual benefits. That is, the combined DOC benefit from the cases mentioned above shows that 5.3% + 1.6% = 3.7% + 3.2%. The order in which these two parameters were considered affects the incremental benefits because of the large weight of acoustic treatment that was added to the high speed baseline airplane. These weight reductions varied non-linearly with the noise reductions associated with blade sweep and advanced precision synchrophasers. The incremental benefits shown in Table 11 account first for advanced precision synchrophasers and then for blade sweep.

Tables 11 and 12 provide a concise summary of the very large effort required by Task II. The tabulated results show that increasing the number of blades in relation to the baseline propellers provided the largest incremental DOC benefits for both airplanes. The effect of increasing the blade number from 3 to 6 improved DOC by 2.7% for the Convair airplane while the change from 4 to 6 blades improved DOC by 9.5% for the Lockheed airplane. The 8 dB reduction in cabin noise levels due to advanced precision synchrophasing improved DOC by 1.0% and 5.3% for the low and high speed airplanes respectively. The tables show that 45° of tip sweep has a 0.1% detremental effect on DOC for the low speed airplane, but that it improved DOC by 1.6% for the high speed airplane. The effects of counter-rotation show that only fuel burned is improved by 0.4% and 1.4% for the low and high speed airplanes respectively and that the on DOC's are higher by 0.4% and 1.2%. These counter-rotation increments were derived for 8-bladed propellers as this number was found to be optimum for both airplanes. Superposition of the incremental benefits in Tables 11 and 12 was still found to be valid for the 8-bladed counter-rotation propellers.

Propeller Parameter Trends: Additional details for some of the many parametric trends summarized in Tables 9 through 12 are shown in Figures 31 through 42. These show DOC and fuel burned improvement variations with total activity factor for each propeller parameter. Those for the Convair airplane are shown in Figures 31 through 37, and those for the Lockheed airplane are shown in Figures 38 through 42. Individual benefits due to number of blades, diameter, sweep, proplets, and advanced precision synchrophasers are shown for both airplanes, and blade material and counter-rotation propeller effects are shown for the low speed airplane. Blade material effects are not explicitly shown for the high speed airplane as only advanced composite blades were considered for these propellers. As a result, each benefit shown in Table 10 and in Figures 38 through 42 includes improvements derived from replacing the solid aluminum baseline propellers with advanced composite blades for the advanced technology propellers. The benefits of counter-rotation for the high speed airplane shown in Table 10 are for but a single propeller configuration. The 6 dB higher far-field noise levels attributed to counter-rotation made it necessary to significantly lower take-off tip speeds to meet the noise requirements for that airplane. The 136 meter per second (445 feet per second) tip speed required for the counter-rotation propellers had an adverse effect on take-off performance of the high speed airplane. The very low tip speed required for this airplane necessitated increasing total activity factor to 1840 for the counter-rotation propeller. This high solidity was necessary to meet the take-off performance and it resulted in a heavy and costly propeller. Wider blades were also examined, but these were excluded from further consideration as they were less efficient at cruise and climb and further increased weight and cost.

The parametric DOC and fuel furned trends shown in Figures 31 through 42 are mainly self-explanatory. It is important to again emphasize that the benefits shown are due not only to the principal parameter(s) on each figure but also to the baseline propeller improvements and to the additional parameters indicated on the figures.

A number of important or interesting observations can be made from the DOC and fuel burned benefit figures and analyses:

1. The propeller configuration which produced the largest DOC benefits are generally close to those which produced the largest fuel burned benefits.

2. The largest DOC improvements for any of the single-rotation, 3.50 meter (11.5 ft) diameter propellers occurred in the 400 to 500 total activity factor range for the low speed airplane.

3. The largest DOC improvements for each 6-bladed propeller configuration occurred at or near 1100 total activity factor for the high speed airplane.

4. Figures 31 and 38 show that 6-bladed propellers provided the largest DOC and fuel burned benefits for both airplanes.

5. Figure 32, for the Convair airplane, shows higher maximas in DOC and fuel burned benefits at each successively larger propeller diameter. It also shows that the propeller total activity factors at these maximas decreased with increasing diameter. The 70 activity factor design constraint (limiting TAF to 420 for 6-bladed propellers) imposed DOC and fuel compromises of only 0.2% and 0.1% respectively for the 3.8 meter (12.5 foot) diameter propeller. The design constraint had no effect at the two smaller propeller diameters.

   Figure 39 shows that the effects of propeller diameter on DOC, fuel burned and total activity factor were not the same for the high speed airplane. The blade thickening required at activity factors below 175 limited the use of high efficiency, thin airfoils to 6-bladed propellers having total activity factors of at least 1050. The high speed propellers were very performance sensitive, and the thickening required for the appropriately lower total activity factors at the larger diameter did not produce benefits that were as high as they would have been with thinner blades

6. Figure 37 shows counter-rotation improved fuel burned for the Convair airplane by 0.4% relative to single rotation, but that the improvement was accompained by a 0.4% increase in DOC. These comparisons, for 3.5 meter (11.5) foot) diameter propellers, were made for the best 6-bladed single rotation and 8-bladed counter-rotation configurations. In order to compensate for the 6 dB higher far-field noise level, the counter-rotation propeller tip speed was decreased by nearly 20% (Table 7). The lower tip speed increased the effective

loading of the propeller and shifted the total activity factor for optimum DOC improvement to 600 (420 for the single rotation propeller). The high speed airplane was more affected by the far-field noise requirement and the required reduction in tip speed of nearly 30% limited the counter-rotation potential and necessitated a very high total activity factor propeller.

A counter-rotation gearbox is expected to be more costly and more complex (higher maintenance cost) than a conventional single rotation gearbox. The degree of this was not established and no reductions in the benefits to account for the counter-rotation gearbox were included in the study.

7. Figures 35 and 42 show that advanced precision synchrophasers provided DOC and fuel benefits for both airplanes. The benefits are defined by the differences between the lines on the figures for the six-bladed propellers with and without advanced precision synchrophasers. The benefits are larger for the high speed airplane as the 8 dB cabin noise reduction has a very powerful weight reduction effect on the heavy acoustic treatment added to that baseline.

   DOC and fuel burned trends for eight-bladed propellers are also shown on these figures. Although both DOC and fuel burned benefits without advanced precision synchrophasers are superior with eight blades, the benefits of synchrophasing, and the total benefits relative to the baseline airplanes are higher for the 6-bladed propellers. This smaller effect for the 8-bladed propellers is due to the lower calculated noise levels (up to 4 dB) which is manifested as less synchrophaser leverage on reducing acoustic treatment weight.

Figures 43 and 44 show airplane DOC, fuel burned, empty weight and acquisition cost trends, propeller efficiency, weight and cost changes and acoustic treatment weight reductions for the two airplanes. These trends are for the advanced technology propeller configurations contained in Table 9, Case 7 for the Convair airplane and in Table 10, Case 6 for the Lockheed airplane. The bullseye symbols on the figures denote the propellers from these two cases which provided maximum DOC improvements relative to the baselines. The resulting additional airplane benefits and associated propeller and acoustic treatment characteristics are denoted by the open symbols. A 6-bladed, 420 total activity factor propeller provided the largest DOC benefit for the low speed airplane. This propeller provided nearly the largest fuel burned benefit with empty weight and acquisition cost improvements within about 1/2% of the maximum benefits. A six-bladed, 1050 total activity factor propeller is both the DOC and acquisition cost optimum for the high speed airplane and provides, within 1/2%, the maximum improvements in fuel burned and empty weight. Propeller mission weighted efficiencies of 8.5% and 5.2% above the baseline levels were calculated for the low and high speed airplanes respectively, and these are close to the maximum efficiencies for these families of propellers. The advanced technology propellers afforded a complete elimination of acoustic treatment for the low speed baseline airplane and more than a 90% reduction for the very heavily treated high speed baseline airplane.

Task III - Advanced Technology Propeller Selection

Introduction

The advanced technology propellers identified in Task II resulted in airplane DOC, fuel furned, empty weight and acquisition cost improvements. The improvements resulted in lighter gross weight airplanes which were resized with smaller engines to maintain the same payload, range and airspeed as the two baseline airplanes.

Single rotation, advanced technology propellers were the primary selections for both the Convair low speed airplane and the Lockheed high speed airplane. The selections were made from the propellers in the Task II parametric study which were calculated to provide the largest DOC improvements for the 100 nautical mile stage lengths with fuel priced at 40¢ per liter ($1.50 per gallon). Each propeller meets the performance and noise level objectives set forth for the STAT commuter airplanes. An alternate counter-rotation propeller was also selected for the Convair airplane. These three propellers are shown in Figure 45.

The airplane resizings performed in the Task II parametric study also require the propellers to be resized in accordance with the smaller engines. This was not done in Task II, and the propeller performance, noise, weight and cost characteristics were calculated for the baseline size (shaft power) of the engines. Propeller resizings, which would have been prohibitively complex for the multi-parametered study, were not expected to have a significant effect on either the relative benefits to the airplanes or the propeller selections. Propeller resizings were performed for the primary selections of advanced technology propellers for the two airplanes. The propeller resizing procedure is detailed in Appendix E, and the DOC, fuel burned, empty weight and acquisition cost benefits for the selected propellers include the resizing effects.

There were second thoughts concerning some aspects of the Task I baseline propeller and airplane definitions. That is, a baseline propeller having round shanks, resulting in decreased aerodynamic performance, was chosen as representative of current technology for the Convair 30 passenger baseline airplane; and 2677 kg (5900 lbm) of fuselage acoustic treatment was added to that defined by Lockheed for the high speed baseline airplane. The effects of these baseline choices on the DOC, fuel burned, empty weight and acquisition cost benefits provided by the selected advanced technology propellers were defined from the incremental benefits defined in Task II and are discussed at various points in the following text. The procedures used to define the benefits relative to the alternate baseline airplanes are presented in Appendix F.

Convair 30 PAX, 0.47 Mach Airplane

The primary selection for the Convair airplane was a single rotation propeller having six, narrow (70 activity factor) unswept blades. The propeller incorporates tip proplets, advanced airfoils, advanced composite blades and an advanced precision synchrophaser and is illustrated on the left in Figure 45. The aerodynamic characteristics of this propeller were optimized to include the most advantageous number of blades, activity factor and camber level from the viewpoint of improving DOC. The blade roots incorporate airfoil section and minimum blade/spinner juncture losses. Operating tip speeds were selected to optimize DOC within the constraint of meeting the required far-field noise levels (FAR 36, Amendment 8, Stage III, minus 8 EPNdB.)

Geometric and operational characteristics of the selected advanced technology propeller and the resulting DOC, fuel burned, empty weight and acquisition cost benefits relative to the baseline airplane are shown in Table 13A (51 units) and Table 13B (English units). The resized propeller has a slightly smaller diameter than the baseline and provides improvements of 8.3% in DOC, 17.0% in fuel burned, 12.0% in empty weight and 2.5% in acquisition cost relative to the study baseline airplane. Had the baseline propeller incorporated the aforementioned root airfoil and blade/spanner juncture improvements, the benefits for this advanced technology propeller would have been reduced and equal to 6.9% in DOC, 13.9% in fuel burned, 11.3% in empty weight and 2.0% in acquisition cost.

The reduced benefits described above are due to smaller advanced technology propeller efficiency improvements when compared to the improved baseline propeller. The effects of the poorer root geometry has been discussed throughout the text and is further illustrated in Figure 46. Here the 3-bladed, round shank baseline propeller defines the reference mission weighted efficiency ($\Delta\bar{\eta} = 0$). The improved baseline, also with 3 blades, improves efficiency by 2.5% while the 4, 6 and 8-bladed propellers, which incorporate improved activity factor and camber levels, additionally increase efficiency.

An 8-bladed, counter-rotation propeller was selected as an alternate choice for this airplane. This configuration, illustrated in the center of Figure 45, also incorporates tip proplets, advanced airfoils, advanced composite blades and an advanced precision synchrophaser. The counter-rotation propeller provides benefits to the airplane which were obtained by adding the counter-rotation incremental effects in Table 11 to those described above for the primary propeller selection. The resulting improvements relative to the baseline airplane are 7.9% in DOC, 17.4% in fuel burned, 10.9% in empty weight and 0.7% in acquisition cost. These improvements are generally lower than those defined for the primary propeller selection, but it was felt that counter-rotation could prove to be very beneficial for a less stringent far-field noise requirement. Had the airfoil root geometry been incorporated in the baseline propeller the airplane improvements with the counter-rotation propeller would have been reduced and equal to 6.5% in DOC, 14.3% in fuel burned, 10.2% in empty weight and 0.2% in acquisition cost.

Bar graphs depicting DOC, fuel burned, empty weight and acquisition cost benefits to the Convair airplane attributed to the two advanced technology propellers are shown in Figure 47. The heights of the bars show the benefits calculated for the single rotation propeller and for the alternate choice counter-rotation propeller. These benefits are shown relative to the Task I study baseline airplane while those relative to the baseline airplane incorporating propellers with improved shank geometry are noted by the small arrows on each bar.

Lockheed 50 PAX, 0.70 Mach Airplane

A single advanced technology propeller selection was made for the Lockheed airplane. This was a single rotation propeller having six, relatively wide (175 activity factor) blades with 45° of tip sweep. This propeller incorporates tip proplets, advanced airfoils, advanced composite blades and an advanced precision synchrophaser and is illustrated on the right in Figure 45. The aerodynamic characteristics of this propeller were optimized to include the most advantageous number of blades, activity factor and camber level from the viewpoint of improving DOC. The operating tip speed of this propeller was selected to optimize DOC within the constraint of meeting the required far-field noise levels (FAR 36, Amendment 8, Stage III, minus 8 EPNdB).

Geometric and operational characteristics of the selected advanced technology propeller and the resulting DOC, fuel burned, empty weight and acquisition cost benefits relative to the baseline airplane are shown in Table 14A (SI units) and Table 14B (English units). The resized propeller has about a 5% smaller diameter than the baseline and provides improvements of 24.9% in DOC, 41.2% in fuel burned, 49.9% in empty weight and 12.0% in acquisition cost relative to the study baseline airplane. Had the baseline airplane incorporated only 680 kg (1500 lbm) of acoustic treatment, as defined by Lockheed, these exceptionally large improvements would have been reduced to approximately 6.6% in DOC, 14.1% in fuel burned and 11.5% in empty weight. Acquisition cost would be 0.4% higher than the baseline airplane.

The much smaller benefits relative to a baseline airplane having only 680 kg (1500 lbm) of acoustic treatment are more in line with those shown for the low speed airplane. It is important to note, however, that calculations indicated a cabin noise level 13 dB above the objective for this baseline airplane. Therefore, the advanced technology propeller provides the much smaller benefits but at the same time suppresses cabin noise to the 85 OASPL objective.

Bar graphs depicting DOC, fuel burned, empty weight and acquisition cost benefits to the Lockheed airplane attributed to the selected advanced technology propeller are shown in Figure 48. The benefits relative to the baseline airplane having 3357 kg (7400 lbm) of acoustic treatment are shown by the height of the bars while those relative to the baseline airplane having only 680 kg (1500 lbm) of acoustic treatment are noted by the small arrows on each bar.

Task IV - Research and Development Needs for Advanced Technology Propellers

Introduction

The study results reported in Task III indicate significant reductions in DOC and fuel burned for the resized Convair 0.47 Mach number 30 PAX aircraft and Lockheed 0.70 Mach number 50 PAX aircraft with advanced technology propellers compared to the current technology propellers on the corresponding baseline aircraft. The design features of these advanced technology propellers contributing to the improvements for both aircraft include increased number of blades, reduced activity factor per blade, advanced airfoils, advanced composite materials and proplets on the blade tips on the Convair propellers and increased number of blades, advanced thin airfoils, advanced composite materials and both proplets and sweep on the Lockheed propellers. These design features taken together provided the improvements in DOC and fuel burned, albeit, their individual contributions were relatively small. Moreover, the twist and camber distributions were fall-outs of the design process. Thus the ingredients of these new propellers include contributions of both current state-of-the-art technology elements and advanced technology elements requiring further research. These latter elements are identified below and research programs aimed at about 5 years in the future are outlined.

The magnitude of the aforementioned reductions in DOC and fuel burned were significantly influenced by the stringent cabin and far-field noise requirements of 85 db OASPL ($\approx$75 dBA) and FAR Part 36 Amendment 8 Phase III minus 8 EPNdB, respectively. Thus, as explained in the text, the benefits of the advanced technology elements investigated singularly and/or in combination were largely determined by these noise requirements. Current studies indicate that cabin noise levels in the 80 to 85 dBA levels will be acceptable for commuter aircraft of the 1985 to 1990 time period. Moreover, from recent meetings of international organizations on aircraft noise it is not likely that far-field noise certification requirements will be lower than FAR Part 36 Phase III minus 4 for these aircraft. Accordingly it is recommended that this study be extended to reinvestigate the benefits of advanced technology propellers on both aircraft based on these more realistic noise requirements.

Nevertheless, based on the specific ground rules, this study covered a broad investigation of the major propeller design parameters and candidate advanced technologies on performance, noise, weight and cost of propellers for the new commuter aircraft that could be developed in the post 1985 time period. It is assumed that parallel engine and airframe advanced technology research would be conducted such that development of an advanced commuter aircraft incorporating propeller, engine and airframe advancements could be launched by this time period.

Airfoil design for reduced noise has not been optimized but methodology is available which can be used. Such concepts as approaching a double circular arc rather than supercritical shape and reducing the "peakiness" of chordwise loading have already been identified as areas where noise reduction potential exists. In addition, phase interference between loading and thickness noise components can be explored.

Task III selections of advanced technology propellers for the Convair aircraft and for the Lockheed aircraft provided the greatest reductions in DOC and fuel burned of the large matrix of propellers investigated. Both propellers include critical technology elements requiring further research as listed in Table 15. The other configuration parameters of the propellers are considered to be current state-of-the-art. This chart summarizes the benefits in DOC and fuel burned for each new technology element established from the study, the applicable aircraft, the areas of required research and development, success probability and current status of each technology research program.

A study of Table 15 indicates that of the five technology elements identified, two are now being researched by NASA. First, sweep technology has been part of the large NASA sponsored Advanced Turboprop Program and is expected to provide the design criteria for application to commuter aircraft propellers. Second, NASA have been sponsoring development of reliable 2-D airfoil design analyses that have application for the design of subsonic airfoil sections for propellers. These analyses have been aimed primarily at the designs of wing sections. Consequently, their application to thickness ratios below five percent needed for high speed propeller has not yet been proven. Thus, in using these methods for designing airfoils for propeller blades, it is essential that the thinner airfoils (below $t/b = 0.06$) from each new family be tested to confirm the design and to acquire off-design performance. At the same time NASA should continue to sponsor development of the 2-D airfoil codes extending application to very thin, $\approx 2\%$ thick, airfoils operating into the transonic range.

The potential benefits of synchrophasers in cancelling near field noise of multi-engine aircraft have been demonstrated sufficiently to indicate that significant reductions in cabin noise may be achieved. Further flight tests are needed to confirm the limited test data and to establish the required phasing accuracy and the important parameters for maximizing noise calcellation.

Although NASA has initiated some work to derive methodology for aerodynamic and acoustic performance prediction and design of the proplet concept as well as some experimental programs, considerably more effort is required before the potentially promising proplet is ready for commercial application. Aerodynamic and acoustic benefits need to be proven through analysis and model testing and the structural viability established.

Next and perhaps the most challenging technology element is the application of existing and emerging composite materials to certain propeller components. This particularly includes the acquisition cost and maintenance and reliability costs which all strongly influence aircraft DOC and fuel burned. Optimizing the blade design so as to obtain the lightest possible blade which meets the structural and performance requirements is of utmost importance when considering advanced technology commuter aircraft propellers. This is because any reduction in blade weight results in weight reductions in the blade retention, barrel, and pitch change system hardware. Furthermore, for a given number of passengers, this reduction in propeller weight translates to lower aircraft gross weight with lower power requirements and further weight reductions in the engine, gear box, engine controls and wing and fuselage structure.

Accordingly, to provide the necessary design criteria on these advanced technology elements for commercial application five years in the future, a number of research and development programs are reconnended.

The recommended budget levels provided herein for each suggested area of further effort are very preliminary estimates of the work envisioned. They have been derived by concensus judgment comparing to similar efforts. They would be subject to change when further study of the technical area is conducted and when a specific program is defined in a statement of work and a plan of test.

Beyond this R&D effort, the advanced technology and current state-of-the-art configuration parameters included in the two advanced propeller systems selected from the study should be incorporated in large scale and proof of concept demonstration hardware. These should be tested in a large wind tunnel to prove aerodynamic performance and aeroelastic stability, and flown on a suitable aircraft to establish the far-field noise signature and the near-field noise on the fuselage and in the cabin.

<u>Advanced Technology Features Requiring Research</u>

<u>Advanced Precision Synchrophaser</u>: Synchrophasing has been available for propeller airplanes for many years. The purpose of this equipment is to reduce cabin noise and vibration by holding the phase relationship between the propellers on an airplane. Early synchrophasers were not capable of holding phase with enough precision to achieve significant noise reductions but were sufficiently accurate to minimize the annoying beats which are caused by varying phase interference between propellers. This lack of phase holding accuracy was due not only to the electronic systems used to provide inputs to the hydraulic controls governing propeller RPM but also to the lack of accuracy of the hydraulic controls themselves.

Early concepts of how a synchrophaser reduced cabin noise were that a phase relationship between sound waves from different propellers caused the reduction by interference effects. The inherent simplistic assumption was that the sound was airborne and the effects of fuselage walls were not considered. However, if this assumption was correct, a phase relationship reducing noise at one cabin location would increase it at another location. Tests conducted on a Lockheed P-3 airplane by Hamilton Standard indicated that a phase relationship existed which reduced noise in a large area of the cabin. Thus, the early concept of how synchrophasing works does not appear correct. Instead, a significant part of the cabin interior noise appears to be structure borne.

Recent tests of the synchrophasing concept have been done by Hamilton Standard in cooperation with the Lockheed-California Company using a de Havilland Dash 7. This work further confirmed the belief that structure borne excitation of the fuselage is a significant factor in establishing the cabin noise level. Also, these tests indicate that the noise reduction potential for two engine airplanes is less than that for four engine airplanes.

Objective - The research objective is to establish the noise reduction potential of of synchrophasing in commuter size airplanes with advanced propellers.

Proposed Program - Existing synchrophasing noise reduction data covers only large airplanes which are not typical of the commuter market. Also, the work done to date merely indicates the synchrophasing potential since the precision systems necessary to demonstrate reduced cabin noise are just now being developed. Therefore, the following program is proposed to establish the potential of synchrophasing for advanced technology commuter airplanes.

In Phase I, tape records will be made of exterior fuselage surface pressures, cabin noise levels and cabin vibration levels simultaneously at many locations on existing commuter airplanes similar in size and structure to the advanced commuter airplanes. Tests will be done at cruise conditions with the RPM of each engine slightly different so that the effects of all combinations of phase relationship between propellers can be recorded in a short time. Noise, vibration and phase angle of each propeller will also be tape recorded. The data will be processed to show the phase relationship which minimizes the noise over the largest area of the passenger cabin. If a phase relationship can be established that indicates significant noise reductions are possible, then Phase II will be conducted. In Phase II a super accurate synchrophasing system will be designed, fabricated and operation verified. This Synchrophaser will be capable of holding phase as accurately as established in Phase I. In Phase III the Phase II Synchrophaser will be installed on the test airplane. This requires that the synchrophaser be suitable for use with the engine and propeller of the test airplane. The Phase I tests will be repeated with the refined system and the tape recordings will be processed to show the actual noise reduction benefits achievable with a synchrophaser. Time and cost estimates for the advanced precision synchrophaser program are shown in Table 16.

Proplets: The use of winglets attached to the tips of aircraft wings to reduce induced losses were conceived and developed by NASA. A similar device, named proplets, was proposed by NASA for propeller tips. For this application, it is projected that proplets will result in reduced noise as well as reduced tip losses. Some NASA sponsored effort to develop design and performance prediction methodology has been initiated and some experimental work is currently underway. Moreover, some work has been underway by both NASA and industry to derive methodology for evaluating the effect of proplets on propeller noise. Based on this early analytical work, the STAT study results have shown significant reduction in DOC and fuel burned with the use of proplets. However, before this attractive concept can be incorporated in production propellers further research is required to develop and refine the analytical design tools and to experimentally demonstrate the effect of proplets on propeller aerodynamic performance and noise as well as their structural reliability. Accordingly, the program outlined below is recommended.

Objectives - The research objectives of the proplet program are: (1) to develop the aerodynamic, acoustic and structural design and performance prediction criteria for propellers incorporating proplets and, (2) to experimentally investigate the effect of proplets on the performance and noise of model propellers for advanced commuter aircraft in the 0.45 - 0.70 Mach number cruise range.

Proposed Program - This program includes the continued development of methodologies for the aerodynamic and acoustic design and performance prediction of propellers with proplets fixed to the blade tips. The work includes evaluation of proplet shape parameters on propeller performance and noise. A further effort will cover the structural design of propellers incorporating proplets.

With new and existing methodologies and test data in hand, two model propellers with proplets will be designed for the 0.45 and 0.70 Mach number advanced commuter aircraft. Conventional propellers will also be designed as comparators. The models will be tested over a wide range of Mach numbers in an appropriate wind tunnel to establish the performance levels with and without proplets. Noise tests for a full range of operating conditions will be performed in a suitable acoustic facility to define near-field and far-field noise spectra and directivities. The resulting noise and performance data will be evaluated with the measurements for the comparator models to establish the benefits of proplets. The measured data will be analyzed, compared to predictions and presented in a final report.

Time and cost estimates of the proplet research program are shown in Table 16.

Advanced Airfoils: Airfoil design analyses, like the Garabedian, Korn and Bauer (GKB) program (Ref. 6) have been proven reliable by correlation with 2-D wind tunnel chordwise pressure distributions and overall lift and drag measurements. Propeller manufacturers have utilized these programs to design special airfoil families for new propellers. These airfoil design codes permit the propeller aerodynamicists and acousticians to design new airfoil families to meet specific requirements depending on the propeller application. While the analyses accurately predict on design performance at subcritical Mach numbers for many airfoils shapes, propeller blades incorporate variations in section thickness ratio, operating Mach number and angle-of-attack (frequently above separation) such that some two-dimensional wind tunnel testing is required. At least 4 to 5 airfoils covering a range of thickness ratios commersurate with propeller blades is required to confirm the designs and to provide performance data over the complete operating range. Three dimensional verification of the airfoil designs will be done on design and test of a model propeller. Two-dimensional data for a few airfoils of the family together with calculated performance for the full family would permit derivation of the airfoil data packs required for the propeller methods.

In the noise control area the theoretically based prediction procedures developed in the past ten years (Ref. 7-9) which show the influence on noise of airfoil characteristics can be explored. An example of this was described in Reference 10 where it was shown that supercritical airfoil shapes would produce significantly more noise than double circular arc or series 16 shapes at high cruise Mach number conditions. Also, it was shown in Reference 10 that uniform chordwise loading should produce lower noise than more typical loading distributions tending to peak near the leading edge of the airfoils. With the new theoretical methods, it is also possible to explore the potential of phase cancellation between loading and thickness (blade volume) noise components. For example, the thickness distribution of an airfoil could be shifted forward and the loading distribution could be shifted aft (via camber) to cause noise reduction by destructive interference of the noise caused by these two parameters.

The validity of the existing noise prediction methodology with respect to the influence of airfoil section will be established in the model propeller test. If deficiencies in the airfoil acoustic design methodology are found in these tests then further methodology refinement may be required.

The program outlined below is required to provide airfoil definition and performance data for a representative application.

Objective - The objective of the advanced airfoil program is to provide performance and noise reduction data on a new family of propeller airfoils for an advanced 0.70 Mach number commuter aircraft application.

Proposed Program - Specifically, the advanced airfoil program covers: (1) a family of a ten airfoils covering a range of thickness ratios from 2% to 20% and designed to meet the performance requirements of a 0.7 Mach number commuter aircraft propeller, (2) the selection and manufacture of five airfoils including chordwise pressure taps and appropriately adapted to accommodate wind tunnel attachment, (3) the test of each airfoil over a range of Mach numbers from 0.30 to 1.1 and angles-of-attack from -10° to beyond stall with measurements of chordwise pressure distributions and lift, drag and moment data, (4) reduction of the test data to nondimensional coefficient form, (5) this evaluation of test data from the standpoint of noise reduction potential analysis of the test data and correlations with predictions and (7) the development of data packs for incorporation in propeller designs and performance predictions. If test results show performance deficiencies in one or two airfoils, these should be redesigned, manufactured and tested to assure the desired propeller performance.

This tests will provide three-dimensional verification of the benefits observed in the two dimensional advanced airfoil analyses and tests, provide noise verification and performance data, and allow comparison of surface pressure measurements to 2D analysis and test results.

The program and approximate costs for the design fabrication testing and data analysis of the advanced airfoils and model propeller are shown in Table 16.

Advanced Blade Structures: The development and production of lightweight composite propeller blades have been actively pursued in the industry since the middle 1940's. Earlier work dealt with the replacement of aluminum alloy blades with the spar shell concept. Fiberglass shell blade development in the 1960's led to propellers in service in the early 1970's. The newer composite blades will address advanced propeller geometry which may incorporate proplets, sweep, and very low activity factor blades.

Hamilton Standard has conducted conceptual studies and analyses of propeller blade designs which provide technological advancements in performance, weight and cost. These studies have resulted in definition of concepts which have the potential of obtaining the desired goals for advanced technology propellers.

Blades with lightened aluminum or steel spars and fiberglass shells can alleviate the inefficient use of spar material in solid metal/fiberglass shell designs. By reducing the spar weight relative to its capacity to react bending loads, considerable weight and cost savings can be achieved.

There are several spar designs which achieve weight reductions relative to a solid spar designs. One method of achieving this is through the use of a hollow spar, as illustrated in Figure 49A and Figure 50. The use of spar material in this design is quite efficient since the spar reacts the flatwise weak axis and the edgewise strong axis bending loads, and possesses high torsional stiffness to avoid the blade instability associated with stall flutter. The ability to vary the spar and shell wall thicknesses independently gives the designer considerable flexibility in addressing specific problems such as high local stresses and fine tuning the blade frequency response. The primary disadvantage of this design is that the spar fabrication techniques, including tube reduction/die forming and machining, are somewhat costly. This problem should be alleviated in time as advances are made in manufacturing processes, especially in the area of numerically controlled machining.

An alternate lightened spar concept is the scalloped spar, illustrated in Figure 49B. Compared to the hollow spar concept, this design has the advantages of being less expensive to fabricate and more easily inspected. In regard to blade frequency response, this design allows a wide variation of the critical speed locations. The main disadvantage of the scalloped spar design is that it is less efficient structurally than the hollow spar concept, especially when considering torsion.

A third lightened spar concept is the built-up box section spar illustrated in Figure 49C. Like the hollow spar, this design incorporates a highly efficient use of spar material while being less expensive to fabricate than the hollow spar. However, this design has potential structural problems at the juncture of the web and flange where direct bending and torsional shear stresses must be transferred through a bond. Given the cyclic nature of the loadings, the potential of bond fatigue fractures does exist.

A second blade design consisting of a shortened hollow steel spar with a Kevlar and graphite/epoxy composite shell has been concepted. This design is illustrated in Figure 51. Since the spar has been shortened the shell is required to carry the structural loads over the majority of the blade length. Composites such as Kevlar and graphite/epoxy can provide specific ultimate strengths and stiffnesses that are unidirectionally higher than metals. However, the transverse properties and the shear strengths of resin/epoxy matrix composites are typically lower. The fibers in this design would be cross-plied to increase the transverse properties at the expense of the maximum unidirectional strength and stiffness. The composite shell layer distribution is shown in Figure 52, and an enlarged view of the spar-shell juncture is shown schematically in Figure 53.

A third design with a composite spar/composite shell shown in Figure 54, offers the greatest weight reduction potential of all the blade design concepts discussed. Possible variations in spar and shell wall thickness, spar length and fiber orientation and material affords considerable flexibility to the blade designer.

A continuing program of design manufacture, development and test is recommended to establish the adequacy of the most promising concepts. Specific program objectives and content are outlined below.

Objective - The objectives of the advanced blade structures program are to establish methodology and to design, analyze, develop, manufacture and test an advanced propeller which displays: (1) 20% lighter than current aluminum spar/fiberglass shell production blades, (2) no operating restrictions due to frequency, and (3) costs which are no more than current comparable production units for aluminum spar and fiberglass shell blades, and (4) to incorporate new blade geometry in the form of proplets, sweep and low activity factor without significantly increasing blade cost.

Proposed Program - In order to provide a systematic definition of the impact of blade design on propeller weight, various blade designs discussed earlier will be studied in the order of the degree of weight reduction anticipated.

A parallel development effort consisting of evaluation of potential lightweight composite materials, i.e., Kevlar, graphite glass and assorted hybrid combinations, specifically for propeller blade application will be conducted. The blades will be designed to the requirements specified for propellers in current production so that comparative fatigue testing can be performed. The resulting design, responsive to the program objectives, will be constructed using appropriate improved manufacturing techniques. These techniques will be somewhat dependent on the concept and materials selected. However, it is anticipated that Automated Machining and Robotic handling techniques will be employed and that these will be considered during the design in an effort to make the most cost-effective blade which is consistent with all other objectives. For example, should a hollow steel spar become the desired spar concept, trade-off studies would be conducted to determine the most effective method of producing the required thin tapered wall tube. The test blades will be subjected to experimental stress analysis (EAS) followed by zero mean and mean stress fatigue testing at the certification level for 50×10^6 cycles and at succeeding levels of 10×10^6 cycles until failure. This testing will confirm the structural integrity of the design.

The proposed program covers (1) the design and development of an advanced lightweight composite propeller blade, (2) the fabrication of 5 blades for ESA and fatigue testing and, (3) a final report summarizing the fatigue tests results.

The program and approximate costs for an advanced blade development are shown in Table 16.

Task V - Current and Advanced Technology Propeller Data Packs

The STAT program required that propeller parametric data, i.e., aerodynamic and acoustic performance, weight, cost, maintenance and reliability, be generated to support the NASA funded studies with airframe and engine contractors. The data was provided in the form of two data packs, and these were available to the contractors through NASA Lewis. The first data pack was for propellers currently in commercial operation and the second data pack was for advanced technology propellers representative of those that could be developed for the mid-to-late 1980's.

Performance characteristics for a large number of propeller configurations were tabulated in the unpublished data pack reports. These were for propellers with 3, 4, and 6 blades for the low speed (0.47 Mach) airplane and for propellers with 4, 6, and 8 blades for the high speed (0.70 Mach) airplane. The data includes the effects of blade sweep and tip proplets on the performance of advanced technology propellers.

Procedures to estimate propeller noise levels in the near and far field and in the airplane cabins were included in each data pack. Improved and revised noise level estimation procedures were incorporated in the second data pack report. These data procedures were most representative of the noise levels for both the current and advanced technology propellers. The effects of operating condition, altitude, diameter, number of blades, blade tip to fuselage clearance, sweep, counter-rotation, proplets and advanced precision synchrophasers on propeller and cabin noise levels were included in the estimation procedures.

The data pack reports provide equations and/or curves which define weights, OEM acquisition costs and maintenance costs for both the current and advanced technology propellers. These included the effects of number of blades, diameter, activity factor, maximum tip speed and shaft horsepower, blade material, blade sweep, proplets, counter-rotation, and advanced precision synchrophasers.

SUMMARY OF RESULTS

Advanced technology propeller parameters calculated to provide potential improvements to the performance and economy of commuter airplanes were identified. Propeller configurations offering maximum DOC improvements were selected for a 30 passenger, low speed airplane and for a 50 passenger, high speed airplane. A propeller technology level representative of the post - 1985 time period was assumed for the study. Stage lengths for the airplanes were defined to be 100 nautical miles and fuel was priced at 40¢ per liter ($1.50 per gallon).

The study results show advanced technology propellers have the potential to improve propeller performance while meeting the stated noise objectives. When applied to commuter aircraft, the improvements can lead to significant reductions in DOC, fuel burned, empty weight and acquisition cost.

Several of the more important results obtained from this study are:

1. Two baseline commuter airplanes were selected as the basis for defining potential benefits of advanced technology propellers. These are a Convair 30 passenger, 0.47 Mach cruise airplane, and a Lockheed 50 passenger, 0.70 Mach cruise airplane.

2. The baseline propeller performance, noise level, weight, and cost characteristics estimated by the airframe companies were modified. The modifications were made by Hamilton Standard to serve as a consistent reference for the STAT propeller parameter assessment study.

3. The noise level requirements set forth for the STAT commuter airplanes are considerably more severe than for existing aircraft. Meeting these far-field and cabin noise level requirements had a large influence on the advanced technology propeller parameters offering the largest airplane DOC and fuel burned improvements.

4. Increasing number of propeller blades compared to the study baseline propellers provided the largest DOC benefits of the parameters investigated. In relation to the 3 and 4-bladed baseline propellers for the low and high speed airplanes respectively, the individual effect of increasing to six propeller blades reduced DOC by 2.7% and 9.5%.

5. Advanced precision synchrophasers, defined to reduce cabin overall sound pressure levels by 8dB, were calculated to reduce DOC by 1.0% and 5.3% for the low and high speed airplanes respectively.

6. Propellers having 45° of tip sweep were found to reduce DOC of the high speed airplane by 1.6% but to increase DOC by 0.1% for the low speed airplane.

7. Eight blades, four front and four rear, was found to be the optimum number for counter-rotation propellers. The individual counter-rotation effects, obtained from comparisons with optimum 6-bladed single rotation propellers, were calculated to be: increased DOC by 0.4% and 1.2% and decreased fuel burned by 0.4% and 1.4% for the low and high speed airplanes respectively.

8. A single rotation propeller having 6 narrow (70 activity factor), unswept blades incorporating tip proplets, advanced airfoils, advanced composite material and an advanced precision synchrophaser was selected for the Convair low speed airplane. The benefits in DOC, fuel burned, empty weight and acquisition cost are 8.3%, 17.0%, 12.0% and 2.5% compared to the study baseline airplane; and 6.9%, 13.9%, 11.3% and 2.0% compared to a baseline airplane having improved shank geometry in the propeller blades.

9. A single rotation propeller having 6 relatively wide (175 activity factor) blades incorporating 45° of tip sweep, tip proplets, advanced airfoils, advanced composite material and an advanced precision synchrophaser was selected for the high speed Lockheed airplane. The benefits in DOC, fuel burned, empty weight and acquisition cost are 24.9%, 41.2%, 49.9% and 12.0% compared to the study baseline airplane. An alternate baseline having 2677 kg (5900 lbm) less acoustic treatment weight than the study baseline was also examined. Cabin noise was 13 dB higher than the study objective with this baseline. The selected advanced technology propeller eliminated the cabin noise exceedance and also provided improvements of 6.6% in DOC, 14.1% in fuel burned and 11.5% in empty weight. Airplane acquisition cost was increased 0.4% with the alternate baseline.

APPENDIX A

ACOUSTIC PERFORMANCE

Introduction

The acoustic study consisted of several elements which were used to define baseline propeller noise levels, establish noise trends with design and operating parameter changes, investigate advanced concepts, define noise reduction of advanced fuselage treatments, and evaluate the benefits of synchrophasing and counter-rotation. In general, the baseline propeller noise levels were established using a comprehensive theoretically based propeller noise prediction method while the rest of the study was done using empirically derived methods.

The propeller noise prediction method is intimately associated with the aerodynamic performance. Thus, noise/aerodynamic performance tradeoffs, can be defined using this methodology. Similarly, the benefits of advanced concepts can be established on the basis of potential noise reduction, which then can be related to a reduction in fuselage sidewall mass required to meet cabin noise level objectives. Thus, the effects of advanced concepts on source noise can be coupled with aerodynamic performance, weight and cost benefits to establish reduced airplane gross weight, improvements in DOC, etc. It is therefore apparent that the propulsor source noise has a significant influence on the airplane optimization.

This appendix describes the elements of the propeller noise estimating procedure, establishes the model for estimating fuselage sidewall acoustic treatment weight and describes the derivation of advanced precision synchrophaser benefits.

Baseline Propeller Noise Levels

The baseline propeller noise levels were estimated using a Hamilton Standard proprietary method. The basis for this method is given in reference 2. This is a strip analysis method with non-compact sources (i.e., the acoustic sources are distributed over the blades in both spanwise and chordwise directions.) Thus, the method is sensitive to both chordwise and radial loading distributions and can distinguish among airfoil sections; take into account details of geometry such as twist, camber, thickness, chord, and sweep; and include the effects of blade loading distributions.

The propeller noise calculation method includes procedures for all the currently recognized significant sources of propeller noise. These include thickness noise, steady loading noise, unsteady loading noise due to ingestion of atmospheric turbulence, unsteady loading noise due to inflow distortion caused by installation effects, non-linear source noise (quadrupoles), and broadband noise. All but the last source give rise to periodic noise which is evident at discrete frequencies that are interger multiples of the propeller rotation rate times the number of blades. The components are added together, taking account of amplitudes and relative phases. The broadband noise spans the audible frequency spectrum. The source characteristics (i.e., whether monopole, or quadrupole), spanwise distribution, and the interaction among the sources give rise to the radiation pattern.

In addition to estimating source noise level and directivity, the noise prediction methodology includes spherical spreading, atmospheric absorption, and ground reflection effects. These allow the estimate of flyover noise levels which simulate the noise which would be measured as for noise certification.

This procedure was used to estimate the near-field and far-field noise levels for the Convair 30 passenger and Lockheed 50 passenger baseline configurations. In each case, the propeller noise levels at the fuselage for a normal cruise condition were estimated. Also, the far-field noise was estimated for two propellers for the FAR Part 36, Amendment 8 noise certification requirements. These resulted in estimated Effective Perceived Noise Levels (EPNL) at approach, take-off, and sideline locations, including ground reflection effects assuming a microphone located at four feet above grass covered dirt.

Since the propeller noise estimating procedure is comprehensive, it is believed that these estimated baseline noise levels are highly representative of those which would occur in an actual installation.

Propeller Noise Trends

Introduction - The comprehensive propeller noise calculation program is expensive to run, both in terms of time required to collect and code the necessary propeller geometry and operating condition information and in terms of computational time. As the study required the investigation of many propeller configuration variations over a range of operating conditions, it would have been prohibitively expensive to conduct the investigations by calculating each point using the comprehensive computer program. The approach used to do the study was to establish noise increments to be added to the comprehensively defined baseline configuration noise levels. These noise increments are based on correlations of noise measurements as well as generalizations based on analytic calculations.

Blade Sweep - The adjustment for blade sweep is a generalization of the comprehensive propeller noise calculation program. This adjustment takes into account the shift in the relative phase of the contributions from each station in the radial integration of noise. As would be expected, sweep effects are more significant for the higher harmonics than for the lower harmonics. For the STAT study, only two levels of blade sweep were considered: zero sweep and 45 degrees of sweep at the blade tip. Thus, to estimate the noise of a swept blade, the noise of a straight blade is first estimated and then adjusted by an increment representing the noise cancellation due to sweeping the blade tip 45 degrees.

For the near-field noise, in cruise, the sweep benefits calculated using the comprehensive propeller noise calculation program were generalized. It was first determined that the noise reduction increment due to sweep was a function of the parameter $(B)(MT)(K)/(MR)/(1-M^2)$, where B is the number of blades, MT is the relative tip Mach number, K is a constant based on the amount of sweep, MR is the tip rotational Mach number, and M is the flight Mach number. Second, increments were calculated for specific combinations of number of blades, rotational tip speeds, and flight speeds. Over the 183 to 224 m/s (600 to 800 ft/sec) tip speed range it was found that the noise reduction due to sweep was a function of only flight speed and number of blades. Thus, the adjustment shown in Figure 55 is based on number of blades and flight speed.

A somewhat different effect is expected during take-off and approach. Due to the generally higher power input and relatively lower flight speeds in take-off the propeller noise is loading dominated. For a given tip speed and flight speed, a propeller blade is optimized at one loading distribution. Thus, the effect of blade sweep becomes a function of blade loading and shows the greatest benefit near the optimum blade loading distribution. For the purposes of this study, the blade design was optimized at a power to diameter squared loading of 45 kw/m^2 (5.625 SHP/ft^2) per blade. Thus, the benefits of sweep are maximum for this loading condition, with reduced benefits at off-optimum conditions. Figure 56 summarizes the benefits of blade sweep on far-field noise used in this study. As for the near-field case, the propeller noise was first estimated as though it was a straight blade and then the benefit of sweep was added as a noise reduction increment.

The use of sweep in reducing propeller noise was illustrated by examples in parametric data pack reports that were provided to NASA-Lewis as a part of Task V of this STAT contract.

Proplets - Proplets are believed to provide noise reduction by creating a loading noise component oriented so that it destructively interferes with the thickness noise of a propeller. Therefore, for a propeller to show an additional benefit, the thickness noise must be dominant. This occurs at tip speeds generally above 244 m/s (800 ft/sec). However, in order to maintain low noise levels on take-off, as required in the STAT contract, propeller designs are forced toward lower tip speeds where loading noise is dominant. No benefit due to interference between the proplets and the thickness noise are likely at the lower speeds. It should also be noted that addition of a tip proplet adds blade volume and thickness noise which detracts from the source interference benefits of the proplet.

Thus, for the purpose of the STAT study, no extra noise reduction was attributed to the use of proplets. Instead, the noise reduction influence of proplets was assumed to result from the enhanced performance obtained from these devices. The improved performance allows a propeller to have a smaller diameter, lower tip speed, and lower horsepower than a conventional propeller. Therefore, the noise of a propeller utilizing proplets was estimated as though it was a conventional propeller and the noise reduction benefits result from the improved propeller aerodynamics.

Dual Counter-Rotation - The noise from dual counter-rotation propellers was established by comparing analytically the noise from a counter-rotation propeller synthesized from two single rotation, interacting propellers and a single rotation propeller having the same total blade count.

To establish the noise from a counter-rotation propeller, it was first assumed that the configuration resembled a single rotor with inlet guide vanes. The wakes from the inlet guide vanes, including both the potential field and the viscous wakes, were estimated in the rotor coordinate system, i.e., taking account of the opposite rotation of the actual upstream rotor to obtain both the proper relative velocity and also the resulting twice the number of blades wake intersections per revolution of the downstream rotor. From these wakes, the periodic unsteady blade loading due to the rotor/wake interactions was estimated and the resulting noise calculated. Finally, the noise from a single upstream rotor was calculated and added to that estimated for the downstream rotor. It should be noted that typically a counter-rotation propeller has a fixed phase relationship between the two rotors. Thus, the blade intersections take place at the same spacial locations. This means that the radiated acoustic field is not symmetrical about the axis of rotation, but exhibits maxima where interaction takes place and minima in-between. Although in principle this directivity can be used to advantage, by orienting the propellers such that a minimum occurs below the airplane to reduce the noise radiated to the ground, for example, in actuality this may be difficult to do. This is because the number of lobes in the directivity pattern is an integral interger multiple of the number of blades. Thus, a six bladed dual rotation propeller will have six lobes at the fundamental (60 degrees spacing), twelve lobes at the second harmonic (30 degrees spacing), etc. It is readily apparent that the spacing quickly becomes too fine to remain in a minimum under typical airplane operating conditions. For the purposes of this study, it was assumed that the noise of dual rotation was always measured on a maxima.

For comparison purposes, the noise of a single rotation propeller having the same total blade count, diameter, tip speed, and total power input was estimated. This was compared to the noise of the counter-rotation propeller. The differences are then the noise increments to be added to the noise of a single rotation propeller to estimate the noise of a dual rotation propeller.

As would be expected, due to the additional sources of noise, a counter-rotation propeller will produce more noise than the equivalent single rotation propeller. Representative increments are 6 dB in the far-field but, with phase cancellation, no increase in the near-field. Even though a counter-rotation propeller will have better aerodynamic performance than a single rotation propeller and thus can be operated at a lower tip speed, the improved performance will generally not be enough to offset the higher noise due to the blade interactions.

Blade Count - The effect of changing numbers of blades can be determined using the noise prediction methodology provided in Task V. This procedure allows noise estimates for 2, 3, 4, 5, 6, and 8 bladed propellers. Thus, the effect of changing number of blades was determined by calculating the noise of a propeller with a different number of blades than that of the base propellers, determing the noise increments due to number of blades and then adding the increments to the baseline propeller noise levels calculated with the proprietary method.

Interior Noise Prediction

The interior noise was estimated using a procedure developed at Hamilton Standard. This procedure allows the calculation of the maximum noise along the cabin centerline (typically in the propeller plane of rotation). It is based on estimating the propeller noise under free-field conditions at the fuselage sidewall location then applying empirical values for the fuselage sidewall noise reduction and the cabin pressurization effects.

In this procedure, the maximum free-field noise incident on the fuselage is estimated. Then the fuselage sidewall noise reduction values are subtracted from the exterior levels. A correction for pressurization effects is added and then the levels are increased to account for the presence of two propellers on the aircraft. The resulting levels are representative of the maximum interior noise levels along the fuselage centerline.

The fuselage sidewall noise reduction values have been derived from a study of interior and exterior noise levels of actual aircraft. The values used are 32 dB for frequencies less than 400 Hz, increasing to 50 dB at 1000 Hz and beyond. These values have been found applicable to pressurized fuselages having round cross-sections. A cabin pressurization correction accounts for the difference in acoustic impedance between the cabin interior and the exterior environment.

This procedure has proved to be remarkably consistent in estimating the interior noise level of turboprop airplanes in cruise. Figure 57 shows a correlation between measured and calculated interior noise levels for propeller driven airplanes. As may be seen, for pressurized fuselages in the 5 to 11 ft. diameter range, the agreement is very good.

Fuselage Sidewall Acoustic Treatment Effects

In order to meet the interior noise level objectives without undue weight penalties, it was necessary to adjust the amount of treatment applied to the fuselage sidewall. This was accomplished by relating the amount of excess attenuation to a weight penalty, both relative to that provided by the conventional fuselage.

In order to establish the relationship between weight and excess attenuation, the assumption that a doubling of the sidewall mass resulted in a 6 dB increase in attenuation (mass law) was used. This led to a relationship of the following form:

$$\Delta dB = 20 \text{ Log}_{10} \left(\frac{Wo + WT}{Wo}\right)$$

where ΔdB is the attenuation provided by WT pounds of additional treatment. W_o is the reference sidewall mass. To establish the value of W_o, the attenuation provided by the airframes was used. Convair indicated that 20 dB additional attenuation would be required and that this would result in an increase in weight of 1054 kg (2324 lbs.) Lockheed's studies indicated 18 dB for 680 kg (1500 lbs.) of treatment. From the above equation, using these values of noise reduction and weights, W_o is 117 kg (258 lbs.) for the Convair baseline airplane and 98 kg (216 lbs.) for the Lockheed baseline airplane.

From the above equation and values for W_o, the weight penalty vs. additional attenuation for each airplane was derived. These relationships are summarized in Figure 3 in the main text of this report. As is readily apparent, the logarithmic function results in small weight penalties for moderate attenuation, but the weight penalty increases rapidly with increasing attenuation.

Noise Reduction by Use of Advanced Precision Synchrophasers

Synchrophasing is the automatic control of the propellers on an airplane such that a predetermined phase relationship between the circumferential blade location is maintained constant. This device results in noise reduction by taking advantage of the interference effects among the propeller noise sources. As is well known, two signals of the same frequency will reinforce when in-phase and cancel each other when out-of-phase. Thus, a synchrophaser can be made to vary the relative phases of the acoustic signal from the propellers operating at exactly the same rpm (i.e., same frequency) and promote mutual interference.

The basis for this approach is a test conducted by Hamilton Standard in 1978. In this test, noise levels were measured simultaneously at the 12 locations in the airplane interior shown in Figure 48. The once-per-revolution pipper signals from the propellers were also received. By purposely applying a slight shift in each propeller speed the relative phase angles, as indicated by the pipper positions, were made to vary slowly. This yielded a variation in interior noise as the relative phase angles changed and produced reinforcements and cancellations for the fundamental blade passage tone as shown in Figure 59. Similar plots were made for other locations and other frequencies. By careful study of these plots, it was possible to select a time when the noise locations was substantially below the peak. For this point in time, the phase angles of the propellers were established. The average noise with the phase angles changing and the noise with the selected phase angles are plotted in Figure 60 for the A-weighted interior level based on the sum of the tones at blade passage frequency, two times blade passage frequency, and three times blade passage frequency. This figure also shows the effect of the accuracy of the synchrophaser, i.e., how well it can maintain the selected phase angles in the noise "valley". From this information, it can be established that a reduction in peak level of 6.5 dB(A) can be obtained with a highly accurate synchrophaser, decreasing to 4.5 dB(A) for a lower accuracy synchrophaser.

For the purposes of the STAT studies, it was assumed that if a synchrophaser were used for noise reduction it would be a unit with high precision, currently feasible using solid-state electronics and high-gain, low-backlash propeller speed governors. Thus, the STAT studies were conducted with the assumption that a synchrophaser would yield a 6.5 dB(A) reduction in interior noise. For a typical interior noise spectrum, this is equivalent to a reduction of 8 dB linear overall level.

Noise Level Requirements

Introduction - The noise level requirements for the STAT study were provided by NASA-Ames. These included interior noise level limits and exterior (flyover) noise level limits. For each case, the acoustic methodology was used to establish the interior noise levels and then define what advanced concepts; additional fuselage sidewall treatment, or synchrophaser were required to reach the objectives. Similarly, flyover noise levels were established and advanced concepts and design tip speeds required to reduce the noise to acceptable levels were defined.

Interior Noise Level Limits - The interior noise level limits were established to be 85 dB linear overall level. This was assumed to be the maximum noise allowable anywhere along the cabin centerline.

Flyover Noise Level Limit - The far-field noise level limits given are based on the FAR Part 36 noise regulations. These stipulate noise level limits for three operating regions, take-off flyover, take-off sideline, and approach flyover. These vary with airplane gross weight and allow trade-offs among the three measurements. Specifically, the noise level limits at any two locations are allowed to be exceeded up to 2 EPNdB provided the exceedances do not sum to more than 3 EPNdB and are completely offset by the noise levels at the other location(s). This trade-off was exercised in this study. The final noise level limits adopted are the Amendment 8, Stage III levels minus 8 dB.

APPENDIX B

AERODYNAMIC PERFORMANCE

Description - The basic aerodynamic design and performance prediction method utilized by Hamilton Standard over the past forty years is a blade element analysis based on the vortex theory of S. Goldstein (Ref. 11) and continually improved as part of ongoing research programs. This theory incorporates a closed solution of the induced flow through the propeller disk for a given operating condition and blade geometry. Airfoil data packs for several airfoil families based on many 2-D wind tunnel tests are included in the program to compute the lift and drag distributions along the blade span. The lift is established at each radial station by an iterative process between the induction analysis and the 2-D data pack for the selected airfoil family. The spanwise thrust and power loadings are then calculated and integrated to define the propeller efficiency at the specified operating condition. This method has been continually improved and refined over the years and has been correlated with wind tunnel test data on many propeller configurations ranging from small models to full scale propellers.

The method has been programmed on the IBM 370 high speed digital computer and is capable of computing over 300 performance points per minute. This excellent, well-proven aerodynamic tool has been utilized to design all propeller configurations developed by Hamilton Standard over the past four decades.

In addition to its use for aerodynamic designs, the code is also used to provide predicted performance over the full spectrum of propeller operating conditions and to provide spanwise loading distribution data required for structural analysis. The code also computes blade aerodynamic twisting moments for retention and pitch change mechanism designs, and various other aerodynamic data including feather drag and windmilling drag.

Aerodynamic Design Procedure - Utilizing the basic propeller performance method described above, the design procedure begins with an initial, preliminary selection of propeller gross shape characteristics including diameter, number of blades, blade planform, thickness distribution, and blade tip sweep. These initial selections are made in consideration of blade structural requirements, performance and noise requirements, and aircraft constraints on maximum diameter. Thus, blade thickness ratio distribution is generally chosen as the minimum allowed by stress limitation, aeroelastic considerations and the fabrication state-of-the-art. The initial blade planform is selected based on experience and a preliminary performance evaluation of the design conditions. The propeller maximum diameter is usually determined by the airframe configuration where fuselage and ground clearance requirements and the number and arrangement of the engine nacelles constrain the selection of maximum propeller diameter. Following the initial propeller selection, the radial gradient of velocity in the propeller plane is next obtained from one of three sources, i.e., a calculation of the flow field around the spinner/nacelle configuration, generalized empirical data, or from the airframe designer. With this velocity gradient, initial selected geometry and design operating condition, the propeller is analyzed using the Hamilton Standard propeller performance method described above.

The optimum loading distribution for minimum induced loss with corresponding minimum profile losses along the blade span is established by iterating between angle-of-attack and camber. If necessary, this iteration process may include variations in planform shape and thickness ratio as permitted by structural considerations. With the blade thus designed, the performance at take-off, climb, and any other important off-design operating conditions is checked for acceptable levels. These results must be coordinated with the acoustic analyses to establish minimum noise levels. If performance or noise levels are not acceptable, further modifications are investigated. Thus, the final iterations of the blade shape are made to assure that the propeller design meets or exceeds all performance and noise level requirements.

The number of blades selection is important to both the aerodynamic and acoustic performance of the propeller. Efficiency and noise levels are usually improved with increasing blade count, but the improvements tend to be off-set by higher propeller weights and costs. The propeller blade element method accounts for number of blades and shows the induced efficiency to be improved for higher blade counts. The higher induced efficiency is due to smaller peaks in the axial and tangential induced velocities which are distributed circumferentially around the propeller disk. The smaller, more numerous peaks integrate to lower induced losses and are a minimum for the classical propeller with an infinite number of blades.

The aerodynamic and the acoustic performance (Appendix A) can be improved by sweeping the propeller blades. The blades are swept to avoid the compressibility drag rise of the airfoil sections for high speed propeller applications. The capability to analyze swept propellers is incorporated into the Hamilton Standard vortex method where the performance for each blade element is calculated for the component of velocity normal to the swept lifting line. Except for a tip correction, which gradually washes out the effect of sweep outboard of the three quarter radius, this amounts to evaluating the airfoil elements at cosine of the local sweep angle times the section relative velocity.

A number of Hamilton Standard Prop-Fan model designs with tip sweep and angles varying from 0° to 45° have been tested. These models were designed for an 0.80 Mach number airplane, and each progressively higher sweep angle produced a higher propeller efficiency.

<u>Method Validation</u> - As pointed out previously, the Hamilton Standard propeller performance method has been undergoing continual refinements since its initial formulation. Moreover, the method has been correlated with extensive wind tunnel test data on many model and full scale propellers. While the basic Goldstein analysis has been retained, several portions of the formulation have been modified to extend the method capabilities both into the low speed and into the high compressible speed ranges. The program correlates well with wind tunnel propeller data over the entire operating range from static to high velocities. The method generally predicts performance levels that are within 1% of the test results near the design conditions. The deviations tend to increase moderately at significantly off-design test points.

Airfoil Performance Requirements - Propellers for advanced commuter aircraft must meet stringent performance and low cabin and far-field noise requirements with minimum weight and cost. High thrust levels for the take-off and climb conditions are essential while maintaining near optimum efficiency at the cruise condition where the blade lift coefficients are often below the design levels. The tip speeds need to be low to achieve the low noise requirements. Moreover, the blades must be narrow to assure minimum weight. These requirements and constraints are unique to the commuter aircraft propellers and led to the selection of high design lift airfoils for this class of propellers. These airfoils must exhibit high lift-to-drag ratios over a wide range of lift coefficients, high critical Mach numbers at lift coefficients both well above and below the design value and high maximum lift coefficients. In addition, the airfoil profiles should be favorable to structural, manufacturing, erosion and FOD requirements. Standard airfoil families like the NACA Series 16 and Series 64, long used in aircraft propellers, have many of these characteristics and have resulted in efficient propellers.

Newer airfoils, like the Liebech, Wortmann, Whitcomb supercritical and the GAW sections, were all designed for special wing requirements and have performed very well. However, none of these have been designed as airfoil families covering a range of thickness ratios required for propeller blades. Moreover, most of the newer airfoils have large nose-down pitching moments or they incorporate profile shapes undesirable from structural, fabrication or maintenance considerations.

The diverse requirements of providing high operating lift coefficients at take-off/climb and low operating lift coefficients at cruise with high lift-to-drag ratios usually cannot be achieved with existing airfoil families. Yet, analysis has shown that specifically designed airfoils can provide high propeller performance levels at the diverse operating conditions. Thus, a new family of airfoils is required to improve performance levels for advanced commuter propellers.

Advanced Airfoil Test Program - Hamilton Standard has undertaken an advanced airfoil development program to design and test a new airfoil family to perform in the manner described above. These airfoils, designated the HS1 Series, were designed specifically to meet the unusual airfoil performance requirements of propellers for advanced commuter aircraft. The HS1 airfoil development program includes: (1) the analytical design of a family of nine airfoils with thickness ratios representative of sections along the blade span utilizing the Bauer, Korn, Garabedian (BKG) airfoil analysis code; (2) the performance prediction of these airfoils over broad ranges of angle-of-attack and Mach number; (3) the design, manufacture and test of six airfoils in a 2-D wind tunnel; and (4) the development of an HS1 airfoil data pack for incorporation into the basic propeller performance program. To date, the nine airfoils have been designed and a preliminary data pack based on calculated performance of these airfoils has been generated. Six 2-D airfoil models have been built including five HS1 airfoil models with thickness ratios of 4%, 6%, 8%, 12%, and 20% and an NASA 16-706 airfoil for reference. Testing is completed and the results have confirmed the design objectives of the HS1 airfoils. For example, the predicted pressure distributions for the cruise, and take-off operating conditions of the HS1-606 airfoil show excellent correlation compared to the experimental data. These data show that there are no shocks on the airfoils and that the measured maximum surface Mach number at the leading edge is below 1.4, and less than predicted. It is concluded that the HS1 airfoils perform somewhat better than originally predicted by the BKG code.

Figure 61 shows a comparison of the test performance on the HS1-606 and the NACA 16-706 airfoils plotted in terms of C_L, C_D, vs. angle of attack at low Mach number and C_L/C_D vs. C_L at high Mach number. This plot clearly demonstrates that the performance of the HS1 airfoil is superior to the comparable NACA Series 16 airfoil.

Model Propeller Performance Test - A test program to demonstrate the projected performance benefits of the HS1 airfoil family was conducted in the UTRC subsonic wind tunnel on two model propellers. One model incorporated the HS1 series airfoils and the other NACA 16 and 64 series airfoils. Otherwise, the models were geometrically identical. Manufacture of the models was completed and testing started about November 1, 1980. Some test results were available before the end of the year.

The propeller models were tested in both throat sections of the UTRC facility in order to completely define the performance characteristics from near static conditions to cruise Mach numbers up to 0.60. The test results were presented (Ref. 12) at the AIAA/SAE/ASME 17th Joint Propulsion Conference. Early evaluation of the model test results have shown that both propellers performed as predicted. Furthermore, the propeller with the HS1 airfoils exhibited the expected performance improvements in relation to the model with the 16 and 64 series airfoils. These observed performance improvements were included as the advanced airfoil benefits to the STAT study propellers.

Propellers with Blade Tip Proplets and Counter-Rotation Blade Rows - It was necessary to go beyond the capability of the programmed methods in order to identify the aerodynamic performance characteristics of some of the advanced technology propeller parameters. Most of the parameters, such as high number of blades, advance airfoils, blade sweep, and thin blades were already within the capability of the method. Counter-rotation propellers and propellers with blade tip proplets, both as shown in Figure 43, were not within the existing capability. These two parameters were treated individually and with procedures that are briefly discussed in the subsequent paragraphs.

Blade Tip Proplets - There have been many attempts to reduce vortex drag by altering wing tip shapes (Ref. 13). Near the turn of the century, Lanchester patented the use of end plates to reduce drag. Since then, many end plate configurations have been proposed. Clements (Ref. 13) showed a marked drag reduction with end plates canted outward 5° and cambered with a 15° trailing edge flap. Whitcomb (Ref. 14) and others investigated end plates called "winglets" and tests suggested that fuel savings due to wing drag reductions of between 7% and 9% could be achieved.

Spillman (Ref. 4) recently reported lift dependent wing drag reductions of up to 30% with the addition of carefully configured wing tip sails. The results that he reported were incorporated into the performance analysis for propellers with prop tip sails, or proplets. The model used in the analysis assumed that the same vortex or lift dependent drag reductions could be achieved on a propeller as on the wings that had been tested. Although the geometry of the wing tip sails reported by Spillman were very complex, Sullivan (Ref. 5) has shown that similar gains, measured in terms of propeller efficiency, are potentially achievable with simpler, single element proplets.

Counter-Rotation Propellers - The counter-rotation propeller performance estimations are based upon efficiency increments added to the vortex strip theory results for single rotation propellers. The increments are the full ideal induced efficiency differences between counter-rotation and single rotation propellers, both calculated by the same method (Ref. 15), and for the same total number of blades. The ideal efficiencies of the counter-rotation propeller are based upon zero swirl loss in the slipstream, a condition which infers that each propeller half absorbs the same torque. This assumption is probably somewhat optimistic at off-design operating conditions. The counter-rotation propeller ideal efficiencies are also based upon axial induced tip losses calculated for half the total number of blades. Since the tip losses diminish with increasing blade number, the counter-rotation benefits thus determined are not as large as would be implied by the full swirl recovery for a given total number of blades.

APPENDIX C

PROPELLER WEIGHT EQUATIONS
(English Units)

The advanced technology, double acting propeller weights for the low and high speed STAT commuter airplanes are given by the following equations. The equations include the blade, hub, pitch change, and spinner weights.

1. Low speed, Convair 30 PAX airplane

W2 = Weight of one single rotation propeller with solid aluminum, unswept blades and no proplets, lbm.

$$W2 = (D^{1.76})(TAF^{.75})(B^{-.05})(UTO^{.5})([M+1]^{.5})(SHPTO^{.12})/1618 \qquad (C1)$$

W1 = Weight of the propellers given by equation (C1) corrected for low activity factor added thickness, lbm.

$$W1 = W2, \text{ if } AF \geq 105 \qquad (C2)$$

$$W1 = (DW\text{-}299\,(AW\text{-}1) + (AW)\,(W2)), \text{ if } AF < 105 \text{ where} \qquad (C3)$$

$$DW = 208\text{-}3.34AF + 1.28\times10^{-2}AF^2 \qquad (C4)$$

$$AW = 1.653\text{-}1.004\times10^{-2}AF + 3.56\times10^{-5}AF^2 \qquad (C5)$$

W = Weight of the above propellers corrected for the inclusion of advanced composite blades, sweep, proplets, and/or counter-rotation, lbm.

$$W = W1 \times WF_n \qquad (C6)$$

where,

WF_n = Product of the weight factors for the advance technology parameters included in the propeller.

WF_1 = .723 (advanced composite blades)

WF_2 = 1.10 (sweep)

WF_3 = 1.05 (proplets)

WF_4 = 1.20 (counter-rotation)

2. High speed, Lockheed 50 PAX airplane

W_2 = Weight of one single rotation propeller with advanced composite, unswept blades and no proplets, lbm.

$$W_2 = (D^{1.846})(TAF^{.75})(B^{-.05})(UTO^{.3})(SHPTO^{.327})/3389 \qquad (C7)$$

W1 = Weight of the propellers given by equation (C7) corrected for low activity factor added thickness, lbm

$$W1 = W2, \text{ if } AF \geq 175 \quad \text{(C8)}$$

$$W1 = (DW-916.5\ (AW-1) + (AW)\ (W2) \quad \text{(C9)}$$

where,

$$DW = 4691-46.42AF + 0.112AF^2 \quad \text{(C10)}$$

$$AW = 6.133-5.072\text{x}10^{-2} + 1.222\text{x}10^{-4}AF^2 \quad \text{(C11)}$$

W = Weight of the above propellers corrected for the inclusion of sweep, proplets and/or counter-rotation, lbm.

$$W = W1 \times WF_n \quad \text{(C12)}$$

where,

WF_n = Product of weight factors for the advanced technology parameters included in the propeller

WF_1 = 1.00 (advanced composite blades)

WF_2 = 1.10 (sweep)

WF_3 = 1.05 (proplets)

WF_4 = 1.20 (counter-rotation)

APPENDIX D

PROPELLER COST EQUATIONS
(English Units)

The advanced technology, double acting propeller costs for the low and high speed STAT commuter airplanes are given by the following equations. The equations include the blade, hub, pitch change, and spinner costs.

1. Low speed, Convair 30 PAX airplane

C1 = Cost of one single rotation propeller with solid aluminum, unswept blades and no proplets, $

$$C1 = 3.75\,(3B^{.75} + 3.5)\,(.9W2 + .1W1) \qquad \text{(D1)}$$

(The weight term in (D1) includes the cost for low activity factor added thickness; equations for W1 and W2 are given in Appendix C.)

C = Cost of the above propellers corrected for the inclusion of advanced composite blades, sweep, proplets and/or counter-rotation, $

$$C = C1 \times CF_n \qquad \text{(D2)}$$

where,

CF_n = Product of the cost factors for the advanced technology parameters included in the propeller

CF_1 = 1.38 (advanced composite blades)

CF_2 = 1.15 (sweep)

CF_3 = 1.15 (proplets)

CF_4 = 1.20 (counter-rotation)

2. High speed, Lockheed 50 PAX airplane

C1 = Cost of one single rotation propeller with advanced composite, unswept blades and no proplets, $

$$C1 = f(D) + \left(\frac{.3625}{W2}\,f(D)\right)\left(W1 - \frac{(D^{1.846})\,(SHPTO^{.327})}{k}\right) \qquad \text{(D3)}$$

where,

for B = 6

f(D) = (10000D + 20000), D in ft.

k = 1.997

for B = 8

f(D) = (14500D - 3000), D in ft.

k = 2.026

C = Cost of the above propellers corrected for the inclusion of sweep, proplets and/or counter-rotation, \$

$$C = C1 \times CF_n \tag{D4}$$

where,

CF_n = Product of cost factors for the advanced technology parameters included in the propeller

$CF1$ = 1.00 (advanced composite blades)

CF_2 = 1.15 (sweep)

CF_3 = 1.15 (proplets)

CF_4 = 1.20 (counter-rotation)

APPENDIX E

PROPELLER RESIZING

The gross weights of the baseline airplanes were affected by the changes in propeller performance, noise, weight and cost defined in Task II. The gross weight changes, as well as changes in DOC, fuel burned, empty weight and acquisition cost, were defined as a result of the propeller improvements and were based upon the sensitivity factors. The airplanes thus resized in Task II were inherently based upon resized engines. The resized engine shaft powers, however, were not incorporated in the propeller performance, noise, weight and cost calculations. To do so would have required iterations between the analysis input powers and the analysis output benefits, and would have been far too costly for the large number of cases studied. The iterations were performed for the two optimum propellers selected for the airplanes in Task III. The effects on the airplane benefits were small, although included, but were important in defining the diameters of the selected propellers.

The iterative process for resizing each propeller is outlined below:

The initial changes in airplane gross weight (ΔGW_i) is given by the initial changes in fuel burned (ΔFB_i) and empty weight (ΔEW_i) calculated in Tasks I and II:

$$\Delta GW_i = \Delta FB_i + \Delta EW_i \tag{E1}$$

The initial changes in engine size (ΔP_i) is based upon the baseline shaft power (P_{BL}), the initial change in gross weight and the baseline gross weight (GW_{BL}):

$$\Delta P_i = P_{BL} \frac{\Delta GW_i}{GW_{BL}} \tag{E2}$$

The initial change in propeller diameter (ΔD_i) is based upon the baseline diameter (D_{BL}) and the initial, relative shaft power change ($\Delta P_i/P_{BL}$):

$$\Delta D_i = D_{BL} \left[\left(1 + \frac{\Delta P_i}{P_{BL}} \right)^{1/2} - 1 \right] \tag{E3}$$

Equation E3 is based upon a constant power loading (P/D^2) which, at a fixed tip speed, maintains the levels of performance and noise calculated in Task II.

The diameter change affects propeller weight (cost is changed also, but is not needed for the iterations). Weights and costs are defined in Appendixes C and D. The propeller weight change, in turn, affects fuel burned and airplane empty weight. The procedure (equation E1 through E3) is repeated until no diameter change is calculated for two successive iterations. For subsequent iterations the baseline (BL) quantities are replaced by the initial (i) quantities, the initial quantities are replaced by the second iteration quantities, and so on.

The fuel burned and empty weight changes used in the Task III propeller resizings were referenced to the airframe company baselines rather than to the modified baselines that were defined in Task I. In this way the propeller resizings were consistent with the engine shaft powers used both in Task II and in the airframers' baseline studies. The initial changes in fuel burned and empty weight used in equation E1 are therefore the sums of the changes calculated in Task I and Task II:

$$\Delta FB_i = (\Delta FB_I + \Delta FB_{II}) \tag{E4}$$

$$\Delta EW_i = (\Delta EW_I + \Delta EW_{II}) \tag{E5}$$

The delta quantities (ΔFB_i, i.e.,) in equations E1 through E5 are dimensional quantities and are calculated from the percentage improvements defined in Tasks I and II.

APPENDIX F

AIRPLANE BENEFITS FOR ALTERNATE BASELINE DEFINITIONS

Initial baseline airplane and propeller definitions were selected from NASA Ames funded airframe studies (Ref. 1 and 2). Baseline propellers were selected and performance, noise level, weight and coat characteristics were defined in those studies by Convair and Lockheed. The fuselages of the baseline airplanes were acoustically treated by the airframes in order to meet an 85dB cabin noise objective. The propeller characteristics and the fuselage acoustic treatment weights were incorporated by Convair and Lockheed into baseline DOC, fuel burned, empty weight and acquisition cost levels. These baseline propeller and airplane characteristics were modified as the principal objective in Task I of this STAT propeller study.

The root geometry of the Convair baseline propeller and the weight of acoustic treatment for the Lockheed baseline airplane were significantly altered in Task I. These alterations were a result of the study groundrules defined by NASA LeRC and the confirmation analyses performed by Hamilton Standard. The structure of the Task II benefit assessment permitted the impact of the baseline alterations to be applied to the benefits derived for the advanced technology propellers selected in Task III.

CONVAIR, 30 PAX, 0.47 MACH AIRPLANE - Convair originally selected propellers having high performance airfoil sections at all blade radii. This baseline selection was modified in Task I to incorporate round shank blades. Mission weighted efficiency was shown (Table 3) to be 2.5% lower as a result of the round shanks, and baseline airplane DOC, fuel burned, empty weight and acquisition cost were adversely affected. The two propeller candidates selected for this airplane, shown in Figure 45, incorporated advanced technology propeller parameters with blades having high performance airfoil shanks.

Had the baseline propeller incorporated airfoil shanks, as originally conceived by Convair, the benefits attributed to the advanced technology propellers selected in Task III would have been reduced by 1.4% in DOC, 3.2% in fuel burned, 0.6% in empty weight and 0.5% in acquisition cost. These benefit changes were shown in Figure 47 and were calculated with the use of the efficiency sensitivity factors in Table 4 for the 2.5% mission weighted efficiency reduction for the wound shank baseline propeller.

LOCKHEED, 50 PAX, 0.70 MACH AIRPLANE - The Task I confirmation analysis indicated that the Lockheed baseline fuselage acoustic treatment material was insufficient to meet the 85dB cabin noise objective. An additional 2677 kg (5900 lbm) of treatment weight was added in Task I to bring the cabin noise level down 13dB to the required level. This additional treatment weight very significantly increased DOC, fuel burned, empty weight and acquisition cost of the high speed baseline airplane. The advanced technology propeller selected for this airplane in Task III was able to show very large benefit improvements.

An alternate baseline airplane, having only the original 680 kg (1500 lbm) of acoustic treatment was included for discussion in Task III. The advanced technology propeller benefits relative to both baseline airplanes were shown in Figure 48 and are much smaller for the alternate baseline. The reductions in benefits were calculated with the use of the weight sensitivity factors in Table 5 and the 2677 kg (5900 lbm) reduction in baseline treatment weight. The benefits relative to this alternate baseline are less by 18.3% in DOC, 27.1% in fuel burned, 38.4% in empty weight and 11.6% in acquisition cost. Although the advanced technology propeller contributed smaller improvements to the airplane, it also suppressed cabin noise by 13dB to the required level.

APPENDIX G

SYMBOLS

AC	Airplane acquisition cost	$
AF	Activity factor per propeller blade = $6250\int(\frac{b}{D})x^3dx$	
AW	Low activity factor propeller weight adjustment factor	
B	Number of propeller blades	
b	Propeller blade element chord	m(ft)
C	Propeller Cost	$
CF	Advanced technology propeller parameter cost factor	
CLD	Propeller blade element camber (section design lift coefficient)	
CL_i	Camber (integrated design lift coefficient) $= 4\int CLDx^3dx$	
CR	Counter-rotation propeller	
D	Propeller diameter	m(ft)
dB	Sound pressure level in dB, re 20 μ Pa	
DOC	Airplane direct operating cost	¢/seat-kilometer (¢/seat-mile)
DW	Low activity factor propeller weight adjustment factor	
EW	Airplane empty weight	kg (lbm)
FB	Fuel burned	kg (lbm)
FOD	Foreign object damage	

GW	Airplane gross weight	kg (lbm)
M	Airplane flight Mach number	
MR	Propeller tip relative Mach number	
MT	Propeller tip rotational Mach number	
OEM	Original equipment manufacture	
P	Propeller shaft power	kw
PAX	Passengers	
SHP	Propeller shaft horsepower	HP
SHPTO	Propeller shaft horsepower at take-off	HP
SR	Single rotation propeller	
T	Propeller thrust	N (lbm)
TAF	Total activity factor = (B)(AF)	
TO	Take-off	
UTO	Propeller rotational tip speed at take-off	m/s (ft/sec)
V	Airplane flight velocity	m/s (ft/sec)
W	Propeller weight	kg (lbm)
WBL	Baseline propeller weight	kg (lbm)
WF	Advanced technology propeller parameter weight factor	
Wo	Fuselage sidewall reference weight relative to acoustic treatment	kg (lbm)

WT	Fuselage sidewall acoustic treatment weight	kg (lbm)
W1	Propeller weight for activity factors at or above the minimum for thin airfoils	kg (lbm)
x	Fraction of propeller tip diameter	
$\Delta\eta$	Change in propeller efficiency relative to baseline propeller at indicated operating condition	%
$\Delta\bar{\eta}$	Change in mission weighted propeller efficiency relative to baseline propeller	%
$\Delta\bar{\eta}_{CR}$	Counter-rotation effect on mission weighted propeller efficiency relative to the same diameter single rotation propeller having the same number of blades and operating at the same tip speed	%
$\Delta\bar{\eta}_{P}$	Proplet effect on mission weighted propeller efficiency relative to the same propeller without proplets and operating at the same tip speed	%
$\Delta\bar{\eta}_{\Omega}$	Propeller tip sweep effect on mission weighted propeller efficiency relative to the same propeller without sweep and operating at the same tip speed	%
η	Propeller efficiency = 100(T)(V)/P	%
$\bar{\eta}$	Mission weighted propeller efficiency	%
Λ	Propeller tip sweep angle in relative velocity frame	deg

Subscripts

BL	Baseline, referring to propeller or airplane
i	Initial

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TABLE 1. TASK I - BASELINE PROPELLER CONFIRMATION FOR CONVAIR 30 PAX, 0.47 MACH AIRPLANE

		CONVAIR ESTIMATIONS	HAMILTON STANDARD ESTIMATIONS
PROPELLER EFFICIENCY	%		
TAKE-OFF		55.3	54 9
CLIMB		82 0	81 0
CRUISE @ 0.47M, 984 KW (1320 SHP) 185 KM (100 N. MILE) STAGE LENGTH		87 5	84.5
CRUISE @ 0 47M 1111 KM (600 N MILE) STAGE LENGTH		88 8	85 7
WEIGHT OF 2 PROPELLERS	KG (LB_M)	197 (435)	271 (598)
OEM COST OF 2 PROPELLERS	$	102,787	17,641
FAR FIELD NOISE	EPNdB		
TAKE-OFF (81 0 REQ'D)		83 0	88 0
SIDELINE (86.0 REQ'D)		85.0	93.4
APPROACH (90 0 REQ'D)		88.0	76.2
CABIN NOISE	dB, OASPL		
REQUIRED		85 0	85.0
UNTREATED FUSELAGE		105 0	97.5
ATTENUATION REQUIRED*		20 0	12.5
ACOUSTIC TREATMENT REQUIRED*	KG (LB_M)	1054 (2324)	383 (844)

*REQUIRED TO REDUCE CABIN NOISE LEVEL TO 85dB

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TABLE 2. TASK I - BASELINE PROPELLER CONFIRMATION FOR LOCKHEED 50 PAX, 0.70 MACH AIRPLANE

		LOCKHEED ESTIMATIONS	HAMILTON STANDARD ESTIMATIONS
PROPELLER EFFICIENCY	%		
TAKE-OFF		51 7	52 6
CLIMB, SL		81.3	80 8
CLIMB, 3048M (10,000 FT)		83 8	83 5
CRUISE @ 0 70M, 2506 KW (3320 SHP) 185 KM (100 N. MILE) STAGE LENGTH		81 8	78 6
CRUISE @ 0 70M 1111 KM (600 N. MILE) STAGE LENGTH		79.3	79 4
WEIGHT OF 2 PROPELLERS	KG (LB_M)	851 (1877)	831 (1833)
OEM COST OF 2 PROPELLERS	$	155,000	165,000
FAR FIELD NOISE	EPNdB		
TAKE-OFF (81 0 REQ'D)		NOT PROVIDED.	89 2
SIDELINE (86 0 REQ'D)		STATED TO MEET	91 0
APPROACH (90.0 REQ'D)		REQUIREMENTS	87 5
CABIN NOISE	dB, OASPL		
REQUIRED		85.0	85 0
UNTREATED FUSELAGE		103.0	116 0
ATTENUATION REQUIRED*		18.0	31 0
ACOUSTIC TREATMENT REQUIRED*	KG (LB_M)	680 (1500)	3357 (7400)

*REQUIRED TO ACHIEVE 85 dB IN CABIN

TABLE 3. TASK I – BASELINE AIRPLANE CONFIRMATION FOR CONVAIR 30 PAX, 0.47 MACH AIRPLANE

PROPELLER CHANGES DUE TO CONFIRMATION

MISSION WEIGHTED EFFICIENCY	$\Delta\bar{\eta}$ = −2.5%
WEIGHT OF 2 PROPELLERS	ΔW = 74 KG (163 LB_M)
OEM COST OF 2 PROPELLERS	ΔC = −\$85,143
ACOUSTIC TREATMENT WEIGHT (DUE TO CABIN NOISE REDUCTION)	ΔW_T = −671 KG (−1480 LB_M)

SENSITIVITIES FOR RESIZED AIRPLANE – 100 N. MILE STAGE LENGTH FOR FUEL @ 39 6¢/ℓ ($1 50/GAL)

	IMPROVEMENTS DUE TO		
% IMPROVEMENT IN	$\Delta\bar{\eta}$ = 1%	$\Delta W + \Delta W_T$ = −45.4 KG (−100 LB_M)	ΔC = −\$10,000
DOC	0 56	0 37	0 18
FUEL BURNED	1 23	0.60	—
EMPTY WEIGHT	0 27	0 99	—
ACQUISITION COST	0 19	0.29	0.59

EFFECTS OF PROPELLER CHANGES ON BASELINE AIRPLANE

		CONVAIR BASELINE	HAMILTON STANDARD BASELINE	% IMPROVEMENT
DOC	¢/SKM (¢/SM)	6.78 (12.56)	6 44 (11.93)	5.0
FUEL BURNED	KG (LB_M)	293 (646)	279 (614)	4.9
EMPTY WEIGHT	KG (LB_M)	8474 (18681)	7426 (16372)	12.4
ACQUISITION COST	$\$/10^6$	3.159	2 895	8.4

TABLE 4. TASK I – BASELINE AIRPLANE CONFIRMATION FOR LOCKHEED 50 PAX, 0.70 MACH AIRPLANE

PROPELLER CHANGES DUE TO CONFIRMATION

MISSION WEIGHTED EFFICIENCY	$\Delta\overline{\eta}$ = −1.85%
WEIGHT OF 2 PROPELLERS	ΔW = −20 KG (−44 LB_M)
OEM COST OF 2 PROPELLERS	ΔC = $10,000
ACOUSTIC TREATMENT WEIGHT (DUE TO CABIN NOISE INCREASE)	ΔW_T = 2677 KG (5900 LB_M)

SENSITIVITIES FOR RESIZED AIRPLANE - 100 N MILE STAGE LENGTH FOR FUEL @ 39 6 ¢/ℓ ($1 50/GAL)

% IMPROVEMENTS IN	$\Delta\overline{\eta}$ = +1%	$\Delta W + \Delta W_T$ = −45 4 KG(−100 LB_M)	ΔC = −$10,000
DOC	0.65	0.31	0.15
FUEL BURNED	1.27	0 46	—
EMPTY WEIGHT	0.22	0 65	—
ACQUISITION COST	0.21	0.21	0.41

EFFECTS OF PROPELLER CHANGES ON BASELINE AIRPLANE

		LOCKHEED BASELINE	HAMILTON STANDARD BASELINE	% IMPROVEMENT
DOC	¢/SKM (¢/SM)	5.13 (9.50)	6 13 (11 35)	−19.5
FUEL BURNED	KG (LB_M)	425 (938)	550 (1213)	−29.3
EMPTY WEIGHT	KG (LB_M)	11369 (25063)	15742 (34705)	−38 5
ACQUISITION COST	$\$/10^6$	5.139	5 812	−13.1

TABLE 5. BASELINE PROPELLER AND AIRPLANE CHARACTERISTICS USED FOR TASK II PARAMETRIC STUDY

		CONVAIR 30 PAX	LOCKHEED 50 PAX
MISSION WEIGHTED EFFICIENCY	%	78 6[1]	79 7[2]
WEIGHT OF 2 PROPELLERS	KG (LB_M)	271 (598)	831 (1833)
OEM COST OF 2 PROPELLERS	$	17,641	165,000
REQUIRED CABIN NOISE ATTENUATION	dB	12 5	31 0
FUSELAGE ACOUSTIC TREATMENT	KG (LB_M)	383 (844)	3357 (7400)
FAR-FIELD NOISE EXCEEDANCES	EPNdB		
TAKE-OFF		7 0	8.2
SIDELINE		7 4	5 0
SUM		14 4	13 2
DOC FOR FUEL @ 39 6¢/ℓ ($1 50/GAL)	¢/SKM (¢/SM)	6 44 (11 93)	6 13 (11 35)
FUEL BURNED FOR 185 KM (100 N. MILE) STAGE LENGTH	KG (LB_M)	279 (614)	550 (1213)
EMPTY WEIGHT	KG (LB_M)	7426 (16372)	15742 (34705)
ACQUISITION COST	$\$/10^6$	2.895	5.812

MISSION WEIGHTED EFFICIENCY DEFINTIONS

(1) CONDITIONS: 0.47 MACH CRUISE, 0.156 MACH TAKE-OFF
$\overline{\eta} = (4 \times \eta_{CRUISE} + \eta_{T\,O.}) - 5$

(2) CONDITIONS 0 70 MACH CRUISE, 0.40 MACH CLIMB
$\overline{\eta} = (\eta_{CRUISE} + \eta_{CLIMB}) - 2$

TABLE 6. SENSITIVITIES FOR RESIZED COMMUTER AIRPLANE

FUEL PRICE 39 6¢/ℓ ($1 50/GAL)
STAGE LENGTH: 185 KM (100 N MILE)

CHANGES FOR 2 PROPELLERS	CONVAIR 30 PAX % IMPROVEMENTS IN DOC	FUEL BURNED	EMPTY WEIGHT	ACQUISITION COST	LOCKHEED 50 PAX % IMPROVEMENTS IN DOC	FUEL BURNED	EMPTY WEIGHT	ACQUISITION COST
1% MISSION WEIGHTED EFFICIENCY INCREASE	0.56	1.23	0 27	0 19	0 65	1 27	0 22	0.21
45 4 KG (100 LB_M) WEIGHT REDUCTION, INCLUDING ACOUSTIC TREATMENT	0.37	0.60	0 99	0.29	0 31	0 46	0 65	0 21
$10,000 OEM COST REDUCTION, INCLUDING PRECISION SYNCHROPHASER	0 18	—	—	0 59	0.15	—	—	0.41

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TABLE 7. MAXIMUM ALLOWABLE TAKE-OFF TIP SPEEDS AS LIMITED BY FAR FIELD NOISE REQUIREMENTS

CONVAIR 30 PAX AIRPLANE

PROPELLER CONFIGURATION			LIMITING TIP SPEED, M/S (FT/SEC)		
DIAMETER M(FT)	TIP SWEEP, DEG	ROTATION	NUMBER OF BLADES		
			4	6	8
3 2 (10 5)	0	SINGLE	216 (710)	215 (705)	250 (820)
3 5 (11 5)	0	SINGLE	226 (740)	227 (745)	250 (820)
3 8 (12 5)	0	SINGLE	233 (765)	241 (790)	251 (825)
3 5 (11 5)	45	SINGLE	236 (775)	239 (785)	271 (890)
3 5 (11 5)	0	COUNTER	— —	166 (540)	183 (600)

LOCKHEED 50 PAX AIRPLANE

PROPELLER CONFIGURATION			LIMITING TIP SPEED, M/S (FT/SEC)	
DIAMETER M (FT)	TIP SWEEP, DEG	ROTATION	NUMBER OF BLADES	
			6	8
3.35 (11 0)	0	SINGLE	165 (540)	163 (535)
3 66 (12 0)	0	SINGLE	177 (582)	175 (573)
3 35 (11.0)	45	SINGLE	184 (603)	179 (586)
3 66 (12 0)	45	SINGLE	190 (623)	189 (621)
3 66 (12 0)	0	COUNTER	— —	136 (445)

NOTE OTHER PROPELLER PARAMETERS (PROPLETS, TOTAL ACTIVITY FACTOR, CAMBER, ADVANCED PRECISION SYNCHROPHASERS, ADVANCED COMPOSITE BLADES AND ADVANCED AIRFOILS) DO NOT AFFECT LIMITING TIP SPEEDS FOR THE STAT STUDY NOISE ANALYSIS

TABLE 8. CRUISE NOISE ATTENUATION REQUIREMENTS AT INDICATED RATIOS OF FAR FIELD NOISE LIMITING TAKE-OFF TIP SPEEDS - WITHOUT ADVANCED PRECISION SYNCHROPHASING

CONVAIR 30 PAX AIRPLANE

PROPELLER CONFIGURATION			NUMBER OF BLADES					
			4		6		8	
			CRUISE/T O. TIP SPEED					
DIAMETER M (FT)	TIP SWEEP, DEG.	ROTATION	1.0	0 8	1 0	0 8	1 0	0 8
3.2 (10 5)	0°	SINGLE	10 8	7 3	4 7	3 6	9 5	4.7
3.5 (11 5)	0°	SINGLE	10.5	6.9	8.4	4.7	7.7	3 6
3 8 (12.5)	0°	SINGLE	12 3	8 4	10 0	5 6	8.4	3 9
3 5 (11 5)	45°	SINGLE	10.1	6 7	7 5	3.5	6 4	2.0
3.5 (11 5)	0°	COUNTER	—	—	3.2	0 5	2.2	-0 8

LOCKHEED 50 PAX AIRPLANE

PROPELLER CONFIGURATION			NUMBER OF BLADES	
			6	8
			CRUISE/T O TIP SPEED	
DIAMETER, M (FT)	TIP SWEEP, DEG	ROTATION	1.0	1.0
3.35 (11.0)	0°	SINGLE	20.8	17.6
3 66 (12.0)	0°	SINGLE	22.5	20.1
3.35 (11.0)	45°	SINGLE	18.3	14 4
3 66 (12.0)	45°	SINGLE	19 3	15.6
3.66 (12.0)	0°	COUNTER	—	12 7

NOTES.

(1) FUSELAGE ACOUSTIC TREATMENT ADDED TO MEET 85dB OVERALL CABIN NOISE LEVEL

(2) ADVANCED PRECISION SYNCHROPHASERS REDUCE ATTENUATION REQUIREMENTS BY 8dB

(3) FAR FIELD NOISE LIMITING TAKE-OFF TIP SPEEDS ARE SHOWN IN TABLE 7

(4) OTHER PROPELLER PARAMETERS (PROPLETS, TOTAL ACTIVITY FACTOR, CAMBER, ADVANCED COMPOSITE BLADES AND ADVANCED AIRFOILS) DO NOT AFFECT ATTENUATION REQUIREMENTS

TABLE 9. ADVANCED TECHNOLOGY PROPELLER CONFIGURATION AND AIRPLANE BENEFIT SUMMARY CONVAIR 30 PAX, 0.47 MACH AIRPLANE

									BEST DOC PROPELLER		% IMPROVEMENTS				% PROPELLER CHANGES/AC			
CASE NO	DIAM., M (FT)	TIP SWEEP DEG	PROPLETS	ADV PREC SYNC	BLADE MAT L	ROTATION	TAF RANGE	NO BLADES	TAF	NO BLADES	DOC	FUEL BURNED	EMPTY WEIGHT	ACQ COST	EFFIC $\Delta\bar{\eta}$	WEIGHT	COST	AC TR WEIGHT
1	3 5 (11 5)	0	NO	NO	SA	SR	300-660	4 6 & 8	425	6[(1)]	5 1	10 6	7 1	1 5	6 0	17 1	107 9	-76 3
	3 5 (11 5)						300-660	4,6 & 8	425[(2)]	8	5 2	11 4	7 1	1 2	6 6	29 6	156 2	-84 1
	3 5 (11 5)						300 660	4 6 & 8	560	8	4 8	11 2	6 0	0 4	7 0	49 3	213 1	-84 1
2	3 5 (11 5)	0	NO	YES	SA	SR	300 660	4 6 & 8	430	6	6 1	12 8	9 2	2 1	6 8	17 2	136 9	-100 0
3	3 5 (11 5)	0	NO	NO	AC	SR	300 660	4 6 & 8	425	6[(1)]	5 6	11 8	9 1	1 5	6 0	-15 1	171 6	-76 3
	3 5 (11 5)						300 660	4 6 & 8	425[(2)]	8	5 7	12 7	9 2	1 0	6 6	- 6 7	235 8	-84 1
	3 5 (11 5)						300 660	4 6 & 8	560	8	5 4	12 6	8 4	0 0	7 0	8 4	311 4	-84 1
4	3 5 (11 5)	0	NO	YES	AC	SR	300 660	4 6 & 8	430	6	6 6	14 8	11 1	1 9	6 8	-15 1	201 7	-100 0
5	3 5 (11 5)	45	NO	YES	AC	SR	300 660	4 6 & 8	450	6	6 5	14 0	10 4	1 4	7 2	- 1 7	234 1	-100 0
6	3 5 (11 5)	45	YES	YES	AC	SR	300 660	4 6 & 8	425	6	7 3	15 8	10 7	1 5	8 7	0 0	251 1	-100 0
7	3 5 (11 5)	0	YES	YES	AC	SR	300 660	4 6 & 8	425	6	7 4	15 9	11 3	1 8	8 4	-11 7	227 3	-100 0
8	3 2 (10 5)	0	NO	YES	AC	SR	300 660	4 6 & 8	550	6[(1)]	6 0	12 4	11 2	1 8	5 3	-20 1	198 9	-100 0
							300-660	4 6 & 8	560	8	6 3	13 8	10 9	1 0	6 8	- 8 4	278 4	-100 0
9	3 8 (12 5)	0	NO	YES	AC	SR	300 660	4 6 & 8	350[(2)]	6	7 1	15 2	11 0	2 0	7 9	- 9 2	210 2	-100 0
							300 660	4 6 & 8	420	6	7 0	14 5	10 7	1 7	8 2	0	250 0	-100 0
10	3 5 (11 5)	0	NO	YES	AC	CR	300 660	6 & 8	600	8	6 2	14 4	10 0	0 1	7 7	8 4	346 6	-100 0

											DOC ¢/SKM (¢/SM)	FUEL BURNED KG (LB_M)	EMPTY WEIGHT KG (LB_M)	ACQ COST $\$/10^6$	PROP EFFIC $\bar{\eta}$ %	PROP WEIGHT KG (LB_M)	PROP COST $	AC TR WEIGHT KG (LB_M)
BASELINE PROPELLER	3 5 (11 5)	0	NO	NO	SA	SR			300	3	6 44 (11 93)	278 (614)	7438 (16400)	2 895	78 6	271 (598)	17600	383 (844)

NOTES

(1) FOR THESE CASES 8-BLADED PROPELLERS PRODUCED THE LARGEST DOC IMPROVEMENTS RESULTS ARE ALSO SHOWN FOR 6 BLADES TO ILLUSTRATE THE BENEFIT INCREMENTS FOR THE OPTIMUM STAT PROPELLER WHICH HAS 6 BLADES

(2) FOR THESE CASES THE LARGEST DOC IMPROVEMENTS OCCURRED FOR BLADE ACTIVITY FACTORS (TAF÷ NO BLADES) WHICH WERE BELOW THE DESIGN LIMIT BENEFITS AT THE TAF LIMITS ARE ALSO SHOWN

SYMBOLS

AC	ADVANCED COMPOSITE BLADES
AC TR	ACOUSTIC TREATMENT
CR	COUNTER ROTATION
SA	SOLID ALUMINUM BLADES
SR	SINGLE ROTATION
TAF	TOTAL ACTIVITY FACTOR
$\bar{\eta}$	MISSION WEIGHTED EFFICIENCY

TABLE 10. ADVANCED TECHNOLOGY PROPELLER CONFIGURATION AND AIRPLANE BENEFIT SUMMARY LOCKHEED 50 PAX, 0.70 MACH AIRPLANE

									BEST DOC PROPELLER		% IMPROVEMENTS				% PROPELLER CHANGES/AC			
CASE NO	DIAM., M (FT)	TIP SWEEP DEG	PROPLETS	ADV PREC SYNC	BLADE MAT L	ROTATION	TAF RANGE	NO BLADES	TAF	NO BLADES	DOC	FUEL BURNED	EMPTY WEIGHT	ACQ COST	EFFIC $\Delta\overline{\eta}$	WEIGHT	COST	AC TR WEIGHT
1	3.66 (12.0)	NO	NO	NO	AC	SR	800-1600	6 & 8	1050	6[1]	17.0	26.9	35.5	9.2	1.4	-40.1	39.4	-84.2
	3.66 (12.0)						800-1600	6 & 8	1150	8	17.5	29.5	39.2	7.1	1.4	-27.3	66.1	-74.3
2	3.66 (12.0)	NO	NO	YES	AC	SR	800-1600	6 & 8	1100	6	22.3	35.0	47.2	12.6	1.5	-39.8	42.4	-87.6
3	3.66 (12.0)	YES	NO	NO	AC	SR	800-1600	6 & 8	1100	6[1]	20.2	33.1	41.0	10.0	3.7	-31.6	55.2	-75.7
	3.66 (12.0)						800-1600	6 & 8	1300	8	20.6	35.5	44.1	7.6	3.8	-18.5	105.5	-85.4
4	3.66 (12.0)	YES	NO	YES	AC	SR	800-1600	6 & 8	1100	6	23.9	38.8	48.9	12.4	3.7	-31.6	58.2	-92.2
5	3.66 (12.0)	NO	YES	YES	AC	SR	800-1600	6 & 8	1050	6	22.7	36.7	47.1	11.5	3.1	-36.6	60.3	-87.6
6	3.66 (12.0)	YES	YES	YES	AC	SR	800-1600	6 & 8	1050	6	24.3	40.5	48.9	11.3	5.2	-28.4	77.0	-92.2
7	3.35 (11.0)	NO	NO	YES	AC	SR	800-1600	6 & 8	1100	6	21.5	32.5	48.9	13.4	-2.0	-49.9	30.9	-90.3
8	3.35 (11.0)	YES	NO	YES	AC	SR	800-1600	6 & 8	1150	6	23.6	37.3	50.2	13.2	1.6	-41.7	47.3	-93.2
9	3.66 (12.0)	NO	NO	YES	AC	CR	1840	8	1840	8	21.1	36.4	49.0	7.2	1.6	-12.7	130.9	-98.0

	DIAM., M (FT)	TIP SWEEP DEG	PROPLETS	ADV PREC SYNC	BLADE MAT L	ROTATION	TAF RANGE	NO BLADES	TAF	NO BLADES	DOC ¢/SKM (¢/SM)	FUEL BURNED KG (LB_M)	EMPTY WEIGHT KG (LB_M)	ACQ COST $\$/10^6$	PROP EFFIC $\overline{\eta}$ %	PROP WEIGHT KG (LB_M)	PROP COST $	AC TR WEIGHT KG (LB_M)
BASELINE PROPELLER	3.66 (12.0)	0°	NO	NO	SA	SR			672	4	6.13 (11.35)	549 (1213)	15711 (34700)	5.812	79.7	830 (1833)	16500	3350 (7400)

NOTE
(1) FOR THESE CASES 8-BLADED PROPELLERS PRODUCED THE LARGEST DOC IMPROVEMENTS. RESULTS ARE ALSO SHOWN FOR 6 BLADES TO ILLUSTRATE THE BENEFIT INCREMENTS FOR THE OPTIMUM STAT PROPELLER WHICH HAS 6 BLADES

SYMBOLS
- AC — ADVANCED COMPOSITE BLADES
- AC TR — ACOUSTIC TREATMENT
- CR — COUNTER ROTATION
- SA — SOLID ALUMINUM BLADES
- SR — SINGLE ROTATION
- TAF — TOTAL ACTIVITY FACTOR
- $\overline{\eta}$ — MISSION WEIGHTED EFFICIENCY

TABLE 11. INCREMENTAL BENEFITS DUE TO OPTIMIZED/ADVANCED PROPELLER PARAMETERS - CONVAIR 30 PAX, 0.47 MACH AIRPLANE

	% IMPROVEMENTS IN			
	DOC	FUEL BURNED	EMPTY WEIGHT	ACQUISITION COST
IMPROVED ROOTS	1.4	3.1	0.7	0.5
INCREASED BLADE NUMBER (FROM 3 TO 6)	2.7	4.9	6.1	1.3
OPTIMUM DESIGN AND TIPSPEED	0.8	2.0	0.2	-0.4
ADVANCED AIRFOILS	0.2	0.6	0.1	0.1
ADVANCED COMPOSITE MATERIAL	0.5	1.2	1.9	-0.1
ADVANCED PRECISION SYNCHROPHASING	1.0	2.2	2.1	0.5
45° TIP SWEEP	-0.1	0.0	-0.7	-0.5
PROPLETS	0.8	1.9	0.3	0.1
COUNTER-ROTATION (8 BLADES)	-0.4	0.4	-1.1	-1.8
DIAMETER OPTIMIZATION	0.4	0.5	-0.4	-0.2

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TABLE 12. INCREMENTAL BENEFITS DUE TO OPTIMIZED/ADVANCED PROPELLER PARAMETERS - LOCKHEED 50 PAX, 0.70 MACH AIRPLANE

	% IMPROVEMENTS IN			
	DOC	FUEL BURNED	EMPTY WEIGHT	ACQUISITION COST
INCREASED BLADE NUMBER (FROM 4 TO 6)	9 5	15 4	19 0	4 9
OPTIMUM DESIGN AND TIPSPEED	6 6	8 8	13 6	5.5
ADVANCED AIRFOILS	0 4	0.6	0.1	0 1
ADVANCED COMPOSITE MATERIAL	0 5	2.1	2 8	-1.7
ADVANCED PRECISION SYNCHROPHASING	5 3	8 1	11.7	3 4
45° TIP SWEEP	1 6	3.8	1 8	-0.2
PROPLETS	0 4	1 7	0 0	-1.1
COUNTER-ROTATION (8 BLADES)	-1 2	1.4	1 8	-5.4

NOTE. ADVANCED COMPOSITE MATERIAL BENEFITS ESTIMATED FROM PROPELLER WEIGHTS AND COSTS FOR LOW SPEED AIRPLANE

TABLE 13A. ADVANCED TECHNOLOGY PROPELLER SELECTION CONVAIR 30 PAX, 0.47 MACH AIRPLANE (SI UNITS)

		MODIFIED BASELINE PROPELLER	ADVANCED TECHNOLOGY PROPELLER	% IMPROVEMENT
DIAMETER	M	3 50	3 47	
NUMBER OF BLADES		3	6	
ACTIVITY FACTOR		300	420	
CAMBER		0 400	0 450	
TIP SPEED (T O /CRUISE)	M/S	256/205	241/219	
SHAFT POWER (T.O./CRUISE)	KW	1573/984	1309/819	
MISSION WEIGHTED EFFICIENCY	%	78 6	87.1	
WEIGHT (2 PROPS)	KG	271	238	
OEM COST (2 PROPS)	$	17600	59600	
CABIN NOISE	dB	85	85	
FUSELAGE ACOUSTIC TREATMENT	KG	383	0	
FAR FIELD EXCEEDANCE	dB	11 4	0	
DOC	¢/SKM	6.44	5 88	8 3
FUEL BURNED	KG	279	229	17.0
EMPTY WEIGHT	KG	7439	6406	12.0
ACQUISITION COST	$	2,895,000	2,815,000	2.5

ADVANCED TECHNOLOGY PROPELLER INCLUDES

- ADVANCED AIRFOILS
- ADVANCED COMPOSITE MATERIAL
- ADVANCED PRECISION SYNCHROPHASER
- PROPLETS

TABLE 13B. ADVANCED TECHNOLOGY PROPELLER SELECTION CONVAIR 30 PAX, 0.47 MACH AIRPLANE (ENGLISH UNITS)

		MODIFIED BASELINE PROPELLER	ADVANCED TECHNOLOGY PROPELLER	% IMPROVEMENT
DIAMETER	FT	11 47	11 40	
NUMBER OF BLADES		3	6	
ACTIVITY FACTOR		300	420	
CAMBER		0 400	0 450	
TIP SPEED (T.O /CRUISE)	FT/SEC	841/673	790/720	
SHAFT POWER (T.O./CRUISE)	HP	2110/1320	1756/1099	
MISSION WEIGHTED EFFICIENCY	%	78 6	87 1	
WEIGHT (2 PROPS)	LB_M	598	525	
OEM COST (2 PROPS)	$	17600	59600	
CABIN NOISE	dB	85	85	
FUSELAGE ACOUSTIC TREATMENT	LB_M	844	0	
FAR FIELD EXCEEDANCE	dB	11.4	0	
DOC	¢/SM	11 93	10 89	8 3
FUEL BURNED	LB_M	614	505	17 0
EMPTY WEIGHT	LB_M	16400	14122	12 0
ACQUISITION COST	$	2,895,000	2,815,000	2 5

ADVANCED TECHNOLOGY PROPELLER INCLUDES:

- ADVANCED AIRFOILS
- ADVANCED COMPOSITE MATERIAL
- ADVANCED PRECISION SYNCHROPHASER
- PROPLETS

TABLE 14A. ADVANCED TECHNOLOGY PROPELLER SELECTION LOCKHEED 50 PAX, 0.70 MACH AIRPLANE (SI UNITS)

		MODIFIED BASELINE PROPELLER	ADVANCED TECHNOLOGY PROPELLER	% IMPROVEMENT
DIAMETER	M	3 66	3 49	
NUMBER OF BLADES		4	6	
ACTIVITY FACTOR		672	1050	
CAMBER		0 286	0 390	
TIP SPEED (T.O /CRUISE)	M/S	220/220	190/190	
SHAFT POWER (T.O./CRUISE)	KW	3281/2505	2981/2276	
MISSION WEIGHTED EFFICIENCY	%	79 7	84 9	
WEIGHT (2 PROPS)	KG	831	448	
OEM COST (2 PROPS)	$	165,000	275,000	
CABIN NOISE	dB	85	85	
FUSELAGE ACOUSTIC TREATMENT	KG	3357	268	
FAR FIELD EXCEEDANCE	dB	10 2	0	
DOC	¢/SKM	6 13	4 85	24 9
FUEL BURNED	KG	550	375	41.2
EMPTY WEIGHT	KG	15740	10070	49 9
ACQUISITION COST	$	5,812,000	5,196,000	12 0

ADVANCED TECHNOLOGY PROPELLER INCLUDES.

- ADVANCED AIRFOILS
- ADVANCED COMPOSITE MATERIAL
- ADVANCED PRECISION SYNCHROPHASER
- PROPLETS
- 45° TIP SWEEP

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TABLE 14B. ADVANCED TECHNOLOGY PROPELLER SELECTION LOCKHEED 50 PAX, 0.70 MACH AIRPLANE (ENGLISH UNITS)

		MODIFIED BASELINE PROPELLER	ADVANCED TECHNOLOGY PROPELLER	% IMPROVEMENT
DIAMETER	FT	12.00	11 44	
NUMBER OF BLADES		4	6	
ACTIVITY FACTOR		672	1050	
CAMBER		0 286	0.390	
TIP SPEED (T.O./CRUISE)	FT/SEC	721/721	623/623	
SHAFT POWER (T.O.)	HP	4400/3360	3998/3053	
MISSION WEIGHTED EFFICIENCY	%	79 7	84 9	
WEIGHT (2 PROPS)	LB_M	1833	987	
OEM COST (2 PROPS)	$	165,000	275,000	
CABIN NOISE	dB	85	85	
FUSELAGE ACOUSTIC TREATMENT	LB_M	7400	590	
FAR FIELD EXCEEDANCE	dB	10 2	0	
DOC	¢/SM	11.35	8 99	24 9
FUEL BURNED	LB_M	1213	826	41.2
EMPTY WEIGHT	LB_M	34700	22200	49 9
ACQUISITION COST	$	5,812,000	5,196,000	12 0

ADVANCED TECHNOLOGY PROPELLER INCLUDES:

- ADVANCED AIRFOILS
- ADVANCED COMPOSITE MATERIAL
- ADVANCED PRECISION SYNCHROPHASER
- PROPLETS
- 45° TIP SWEEP

TABLE 15. ADVANCED TECHNOLOGY PROPELLER RESEARCH NEEDS – AERODYNAMICS, ACOUSTICS, STRUCTURES

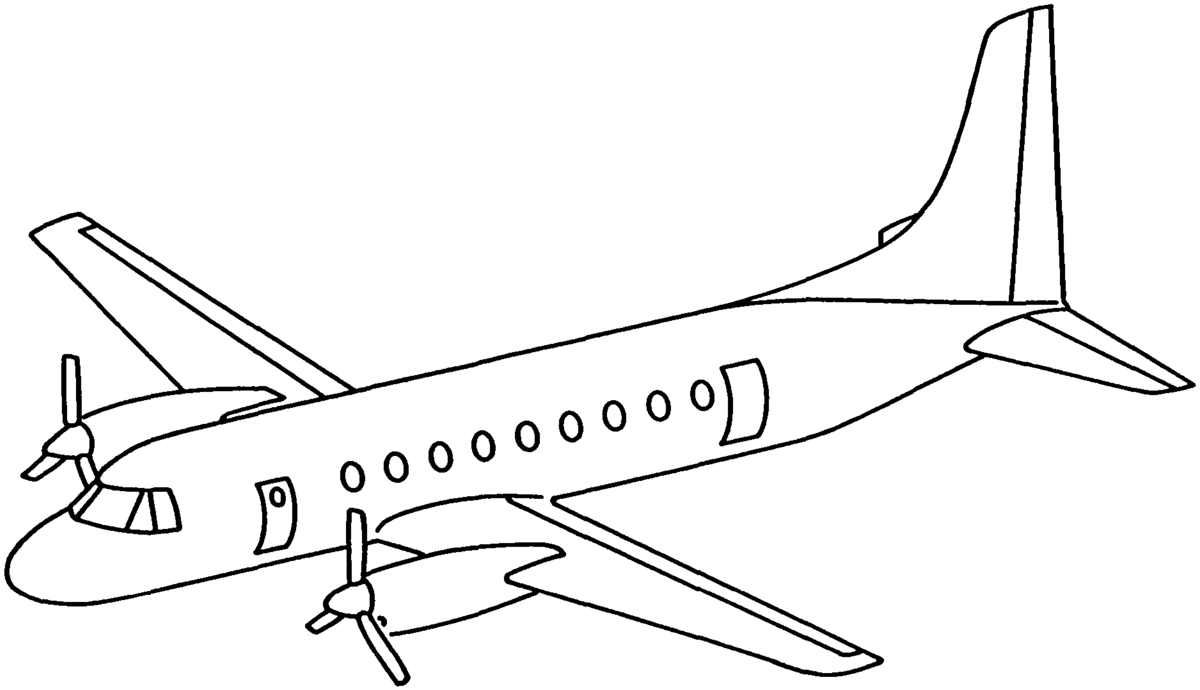
TECHNOLOGY	AIRCRAFT APPLICATION	BENEFITS – %		REQUIRED RESEARCH			SUCCESS PROBABILITY	STATUS
		DOC	FUEL BURNED	ANALYSIS	TEST	STRUCTURES		
BLADE SWEEP	HIGH SPEED	1 6[1] (0 8)	3 8[1] (2 0)	✓	✓	✓	1	NASA SPONSORED RESEARCH ADEQUATE
ADVANCED AIRFOILS	HIGH SPEED LOW SPEED	0.4 0.2	0 6 0 6	✓	✓	✓	1	TESTING REQUIRED FOR EACH NEW BASIC AIRFOIL
ADVANCED PRECISION SYNCHROPHASERS	HIGH SPEED LOW SPEED	5.3[1] (1 0) 1 0	8 1[1] (2.3) 2 0	✓	✓	✓	1	SOME PROOF OF CONCEPT TESTING HAS BEEN DONE, BUT MORE IS REQUIRED TO CONFIRM CABIN NOISE REDUCTIONS FOR MULTI-ENGINED AIRCRAFT
PROPLETS	HIGH SPEED LOW SPEED	0.4 0 8	1 7 1 9	✓	✓	✓	2	RESEARCH INITIATED BY NASA. RIGOROUS AERODYNAMIC AND ACOUSTIC THEORY NEEDED TESTS REQUIRED TO PROVE PERFORMANCE, NOISE AND STRUCTURES
ADVANCED BLADE MATERIALS AND FABRICATION	HIGH SPEED LOW SPEED	0 5[2] 0 5[2]	2 1 1 2	NOT REQUIRED	✓	✓	1	COMPOSITE BLADES ARE EMERGING AS REPLACEMENTS FOR METAL DESIGNS OPTIMUM MATERIALS AND FABRICATION TECHNIQUES NEED STUDY AND TEST FOR ADVANCED BLADE GEOMETRIES

(1) THESE BENEFITS ARE RELATIVE TO HIGH SPEED BASELINE AIRPLANE WITH 3350 KG (7400 LBM) OF FUSELAGE ACOUSTIC TREATMENT BENEFITS ESTIMATED FOR THE ORIGINAL TREATMENT WEIGHT OF 680 KG (1 500 LBM) ARE SHOWN IN PARENTHESIS BASELINE AIRPLANE WITH LOWER TREATMENT WEIGHT EXCEEDS CABIN NOISE OBJECTIVE FOR THE STAT STUDY BY 13 DB

(2) THESE DOC BENEFITS INCLUDE THE HIGHER ACQUISITION COSTS OF ADVANCED COMPOSITES USED IN TASKS II AND III BENEFITS WOULD BE 0 8% FOR NO COST INCREASE COMPARED TO SOLID ALUMINUM BLADES

TABLE 16. ADVANCED PROPELLER TECHNOLOGY RESEARCH PROGRAM

TECHNOLOGY AREA	YEARS FROM START					FUNDING $K
	1	2	3	4		
ADVANCED PRECISION SYNCHROPHASER						
PHASE I						200
PHASE II						300
PHASE III						400
PROPLETS						1500
ADVANCED AIRFOILS						
2D AIRFOIL TEST AND ANALYSIS						400
WIND TUNNEL MODEL						800
ADVANCED BLADE						1800



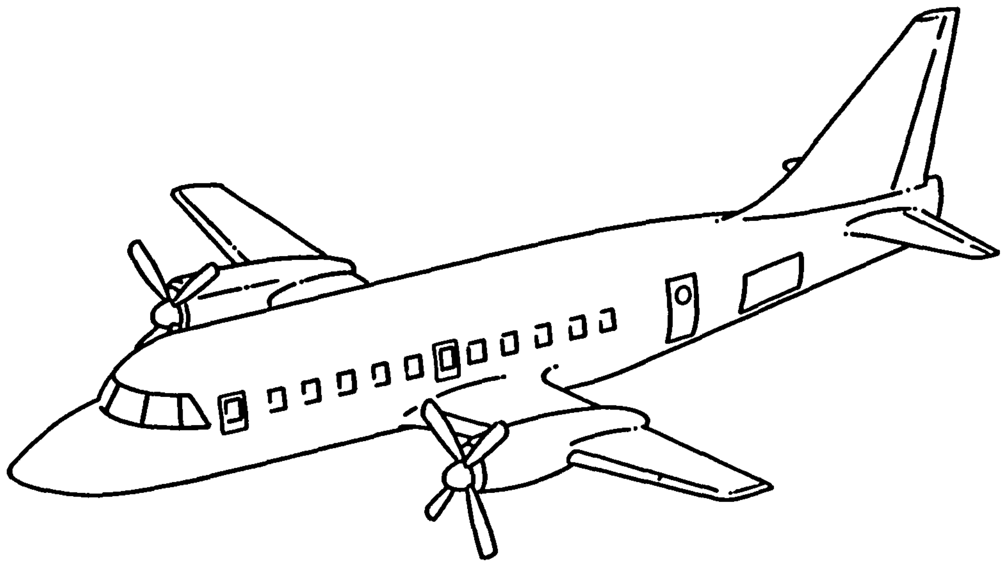
AIRPLANE

CRUISE MACH = 0.47
GROSS WEIGHT = 12700 KG (28000 LBM)
WING LOADING = 2394 N/M^2 (50 LB/FT^2)

PROPELLER

NO. BLADES = 3
ACTIVITY FACTOR = 100
DIAMETER = 3 50M (11.5 FT)
SOLID ALUMINUM BLADES
SINGLE ACTING

FIGURE 1. CONVAIR 30 PAX BASELINE AIRPLANE



AIRPLANE

CRUISE MACH = 0.70
GROSS WEIGHT = 17460 KG (38500 LBM)
WING LOADING = 3830 N/M^2 (80 LB/FT^2)

PROPELLERS

NO. BLADES = 4
ACTIVITY FACTOR = 168
DIAMETER = 3.66M (12 0 FT)
SOLID ALUMINUM BLADES
DOUBLE ACTING

FIGURE 2. LOCKHEED 50 PAX BASELINE AIRPLANE

STUDY BASELINE

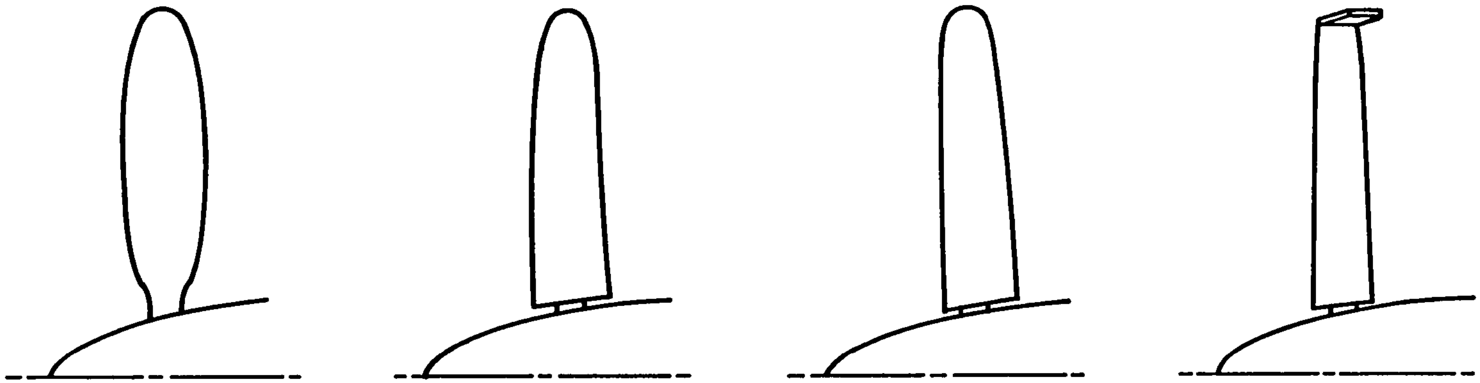
CURRENT GENERAL AVIATION TECHNOLOGY	IMPROVED COMMUTER TECHNOLOGY	INTERMEDIATE ADVANCED TECHNOLOGY	STAT ADVANCED TECHNOLOGY
			
• 3 BLADES	3 BLADES	3 BLADES	6 BLADES
• 100 ACTIVITY FACTOR	100 ACTIVITY FACTOR	100 ACTIVITY FACTOR	75 ACTIVITY FACTOR
• CONVENTIONAL AIRFOILS	CONVENTIONAL AIRFOILS	FIRST GENERATION ADVANCED AIRFOILS	SECOND GENERATION ADVANCED AIRFOILS
• ROUND SHANKS	AIRFOIL SHANKS	AIRFOIL SHANKS	AIRFOIL SHANKS
• SOLID ALUMINUM	ALUMINUM SPAR AND FIB ERGLASS SHELL	ALUMINUM SPAR AND FIBERGLASS SHELL	ADVANCED COMPOSITES
• SINGLE ACTING	SINGLE ACTING	DOUBLE ACTING	DOUBLE ACTING
• –	–	PRECISION SYNCHROPHASING	PRECISION SYNCHROPHASING
• –	–	–	NASA PROPLETS
• 1940–1980+	1975–1985	1985+	1990

FIGURE 3. PROPELLER TECHNOLOGY LEVEL COMPARISON FOR 0.47 MACH 30 PASSENGER AIRPLANE

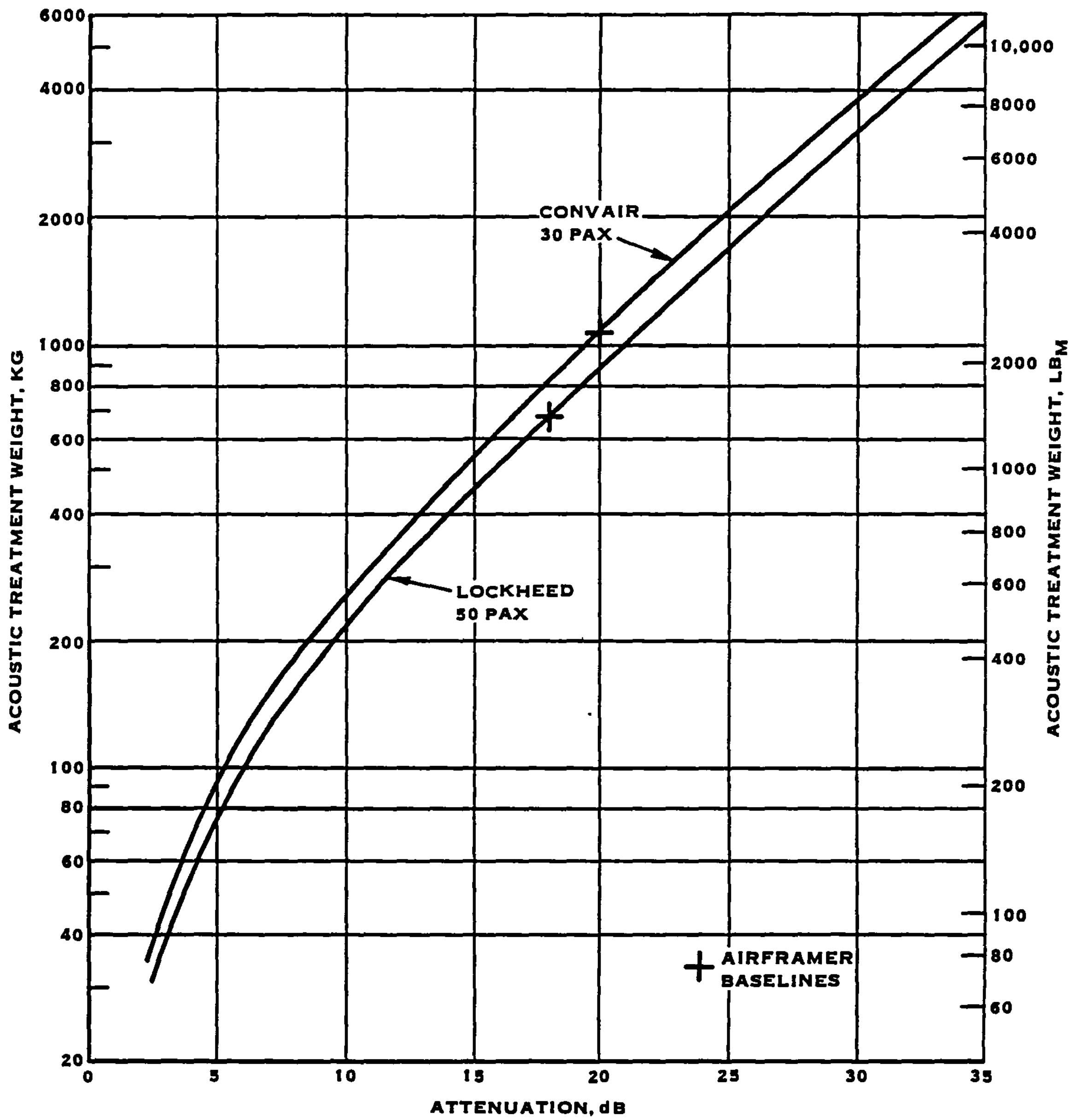


FIGURE 4. FUSELAGE SIDEWALL ACOUSTIC TREATMENT WEIGHT VS. CABIN NOISE ATTENUATION

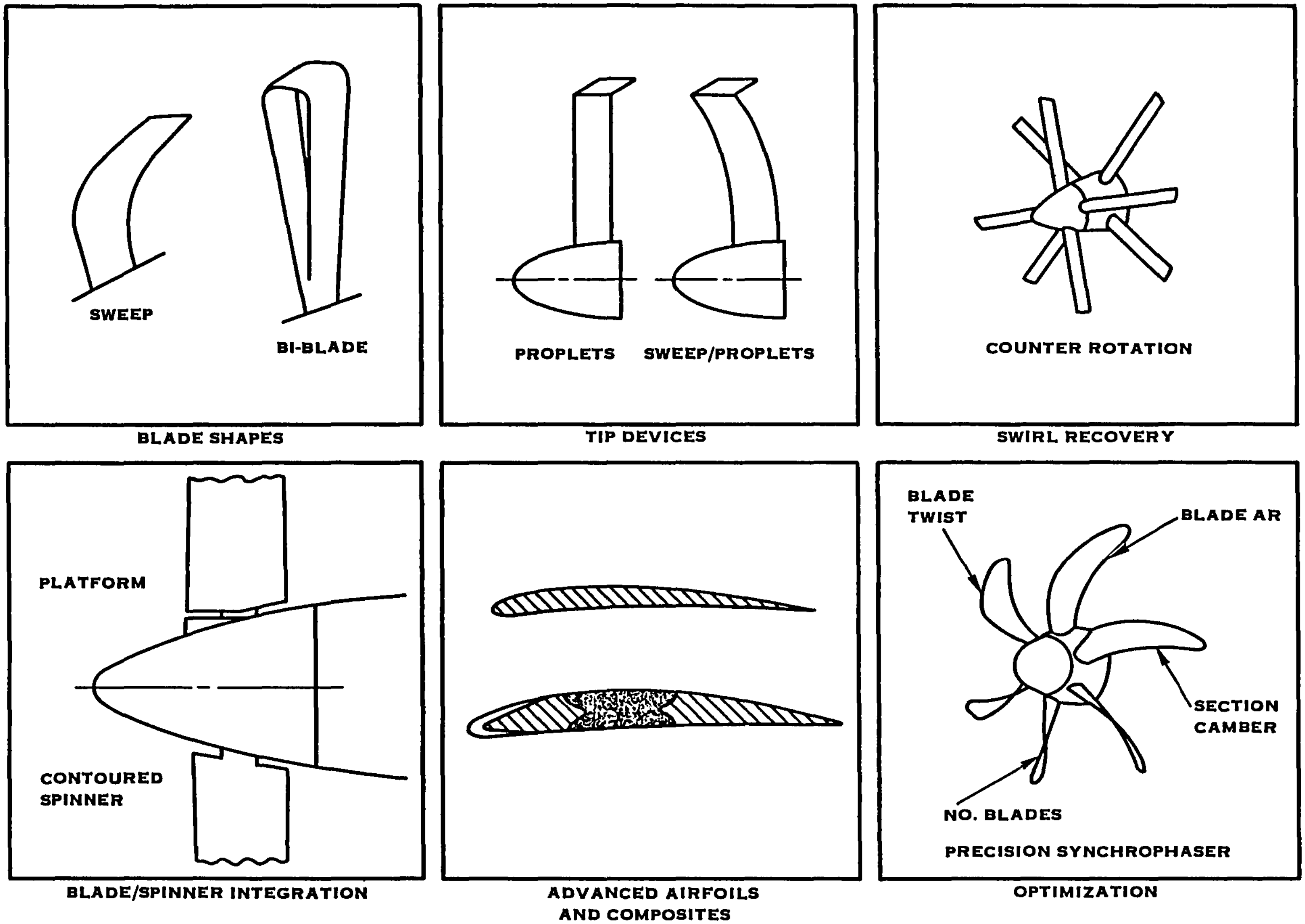


FIGURE 5. ADVANCED PROPELLER CONCEPTS

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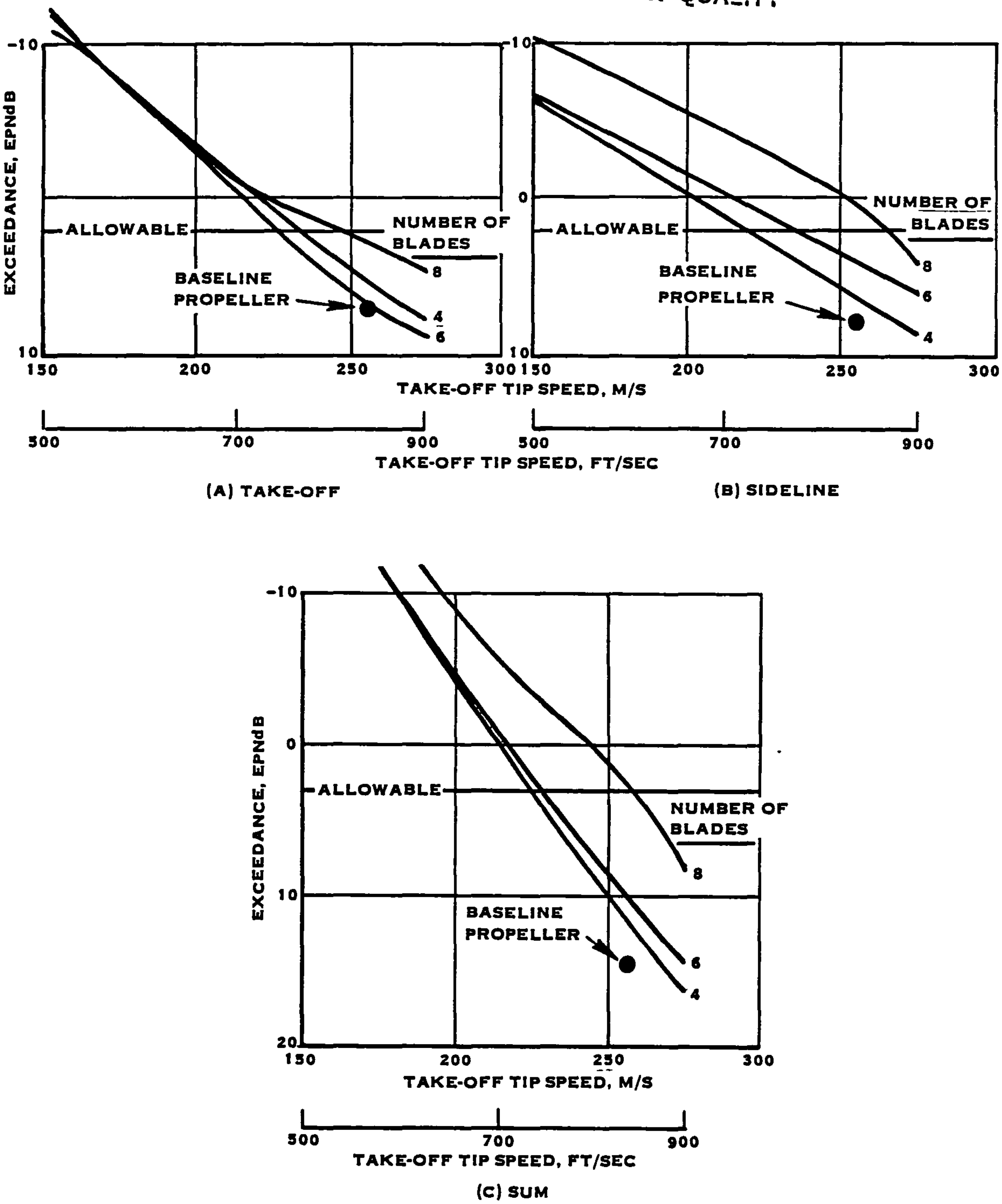

FIGURE 6. EFFECT OF BLADE NUMBER AND TIP SPEED ON FAR-FIELD NOISE; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ANY TOTAL ACTIVITY FACTOR

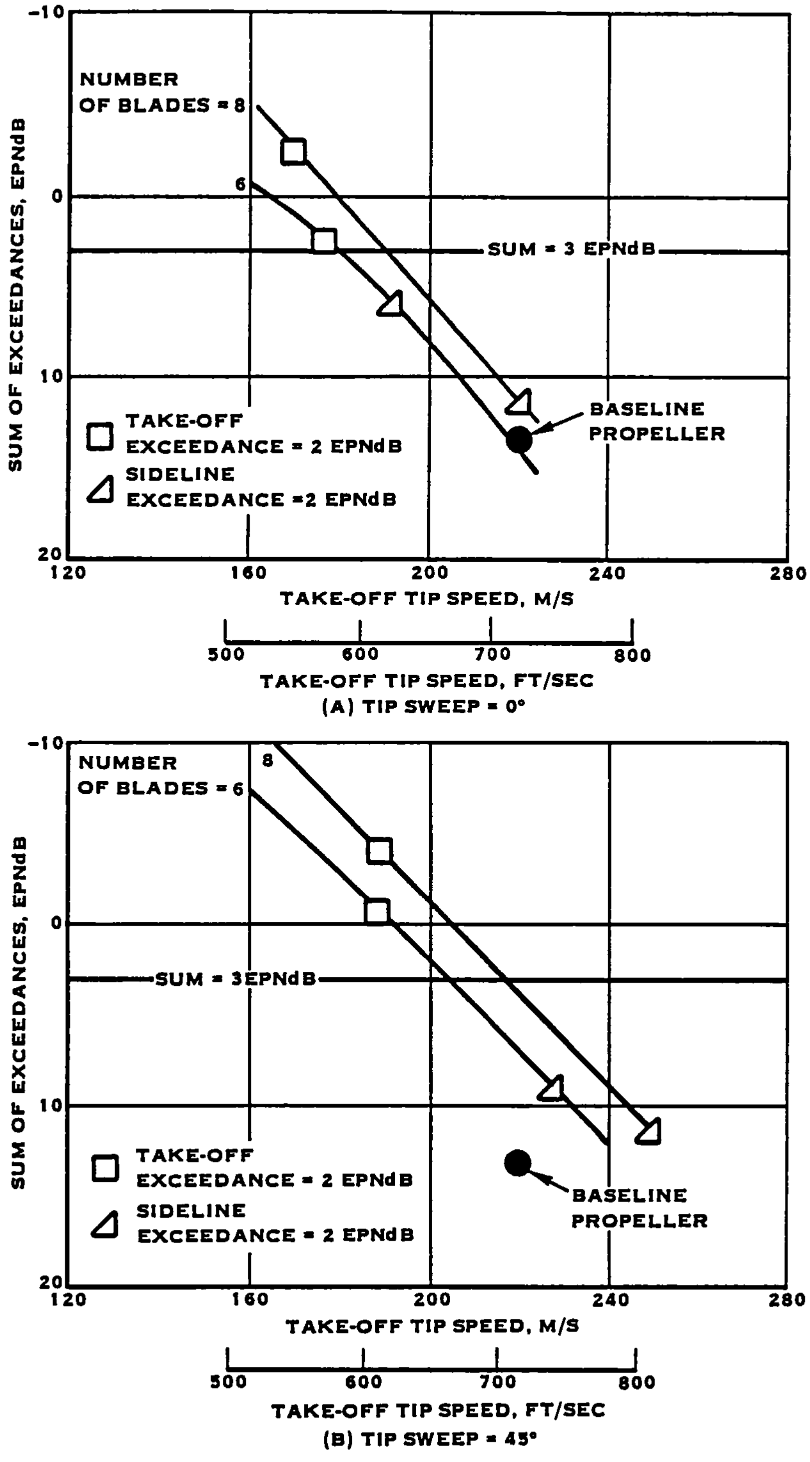

FIGURE 7. EFFECT OF BLADE NUMBER AND TIP SPEED ON FAR-FIELD NOISE; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, ANY TOTAL ACTIVITY FACTOR

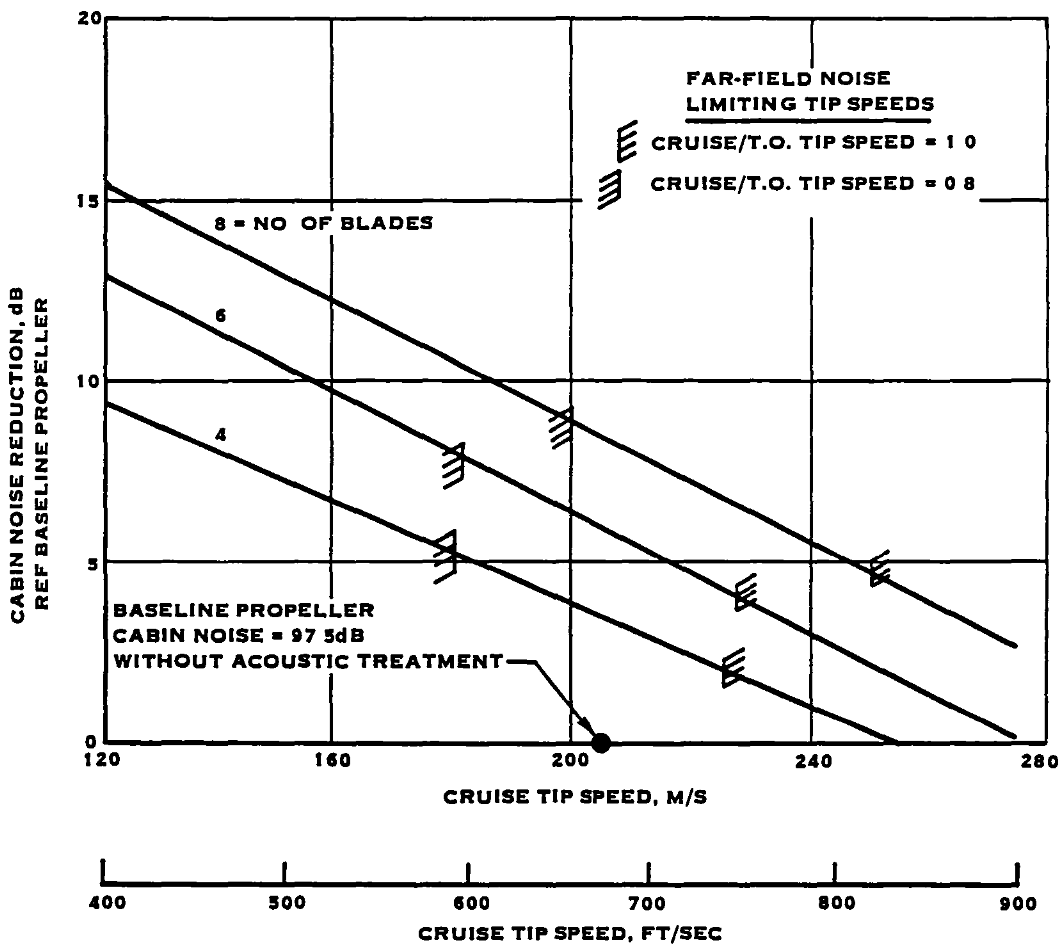

FIGURE 8. EFFECT OF BLADE NUMBER AND TIP SPEED ON CABIN NOISE; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ANY TOTAL ACTIVITY FACTOR

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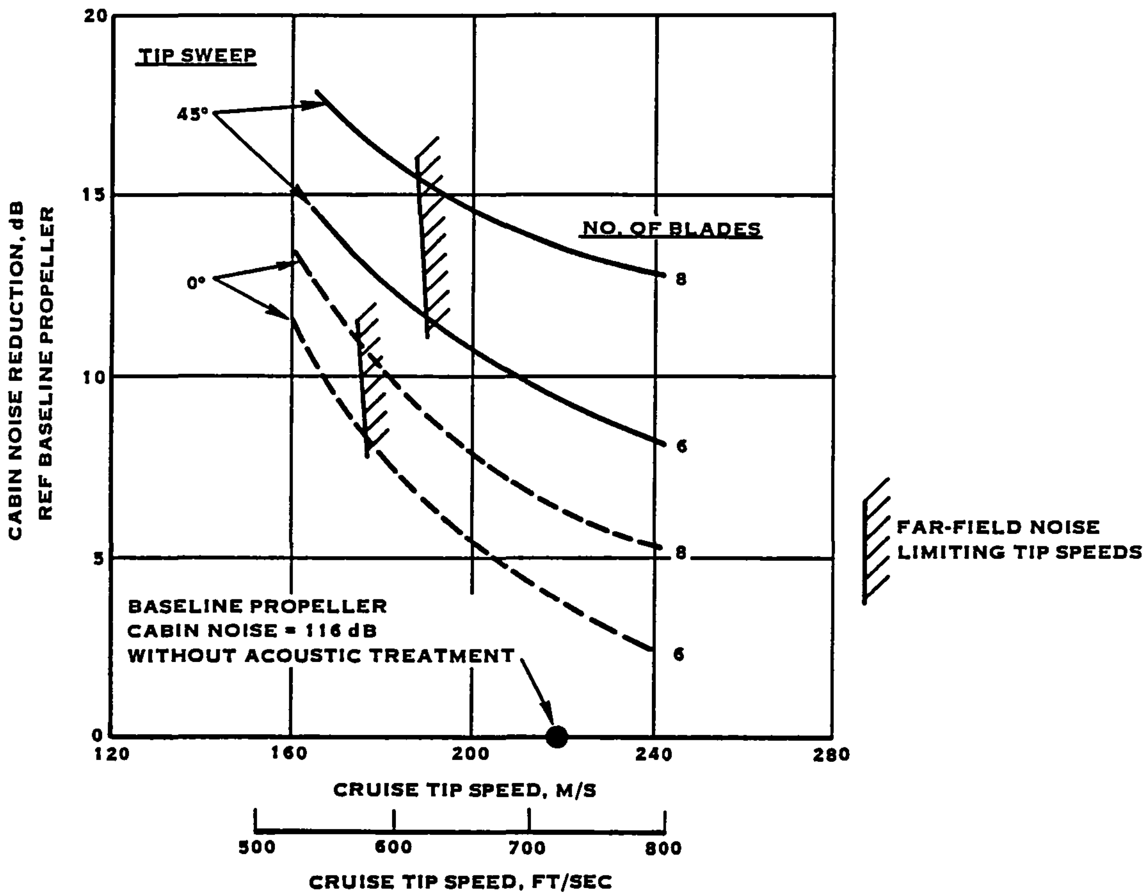
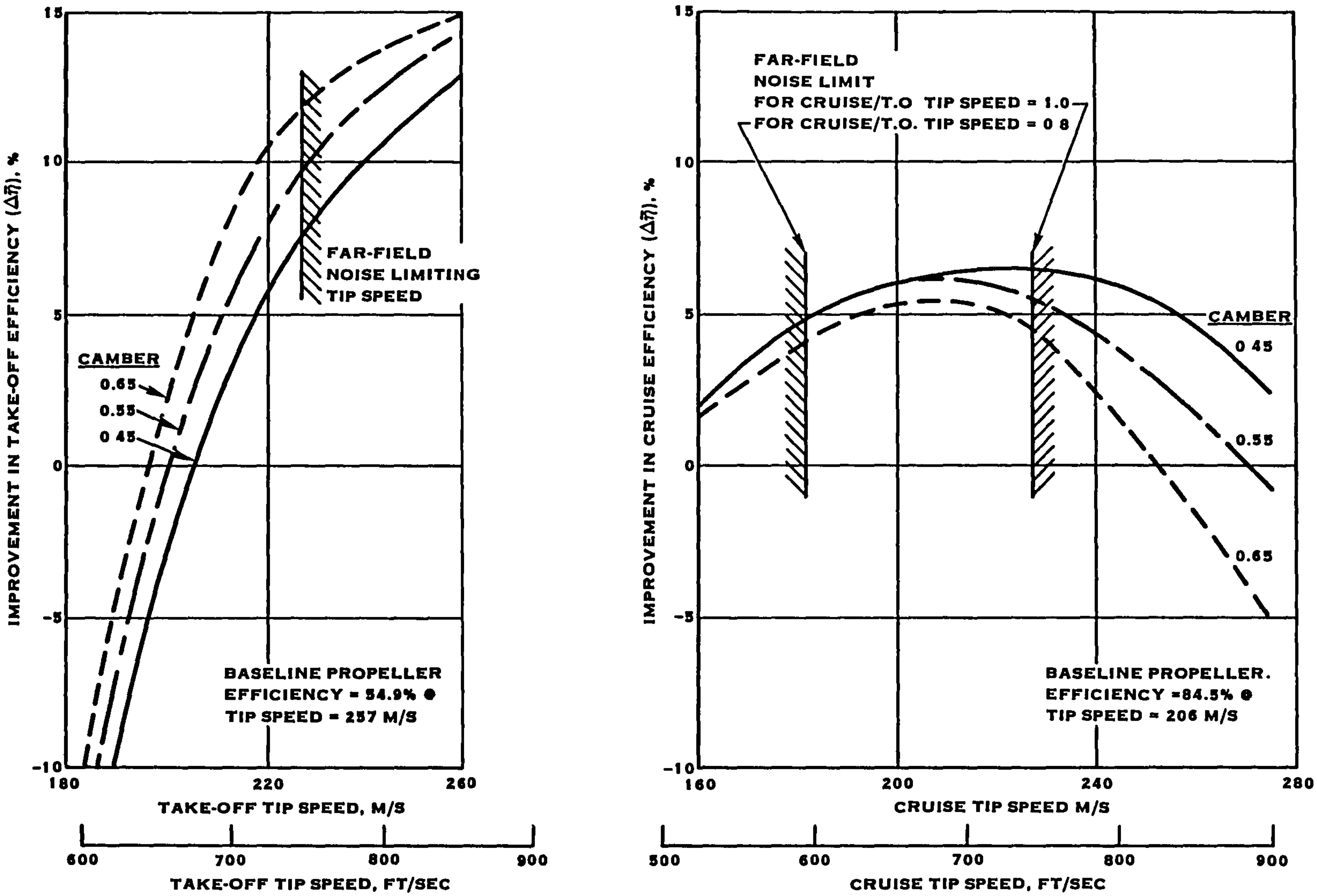


FIGURE 9. EFFECT OF BLADE NUMBER, TIP SPEED AND TIP SWEEP ON CABIN NOISE; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, ANY TOTAL ACTIVITY FACTOR



(A) TAKE-OFF/CLIMB (B) CRUISE

FIUGRE 10. EFFECT OF CAMBER AND TIP SPEED ON PROPELLER EFFICIENCY; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 420, ADVANCED AIRFOILS, IMPROVED ROOTS

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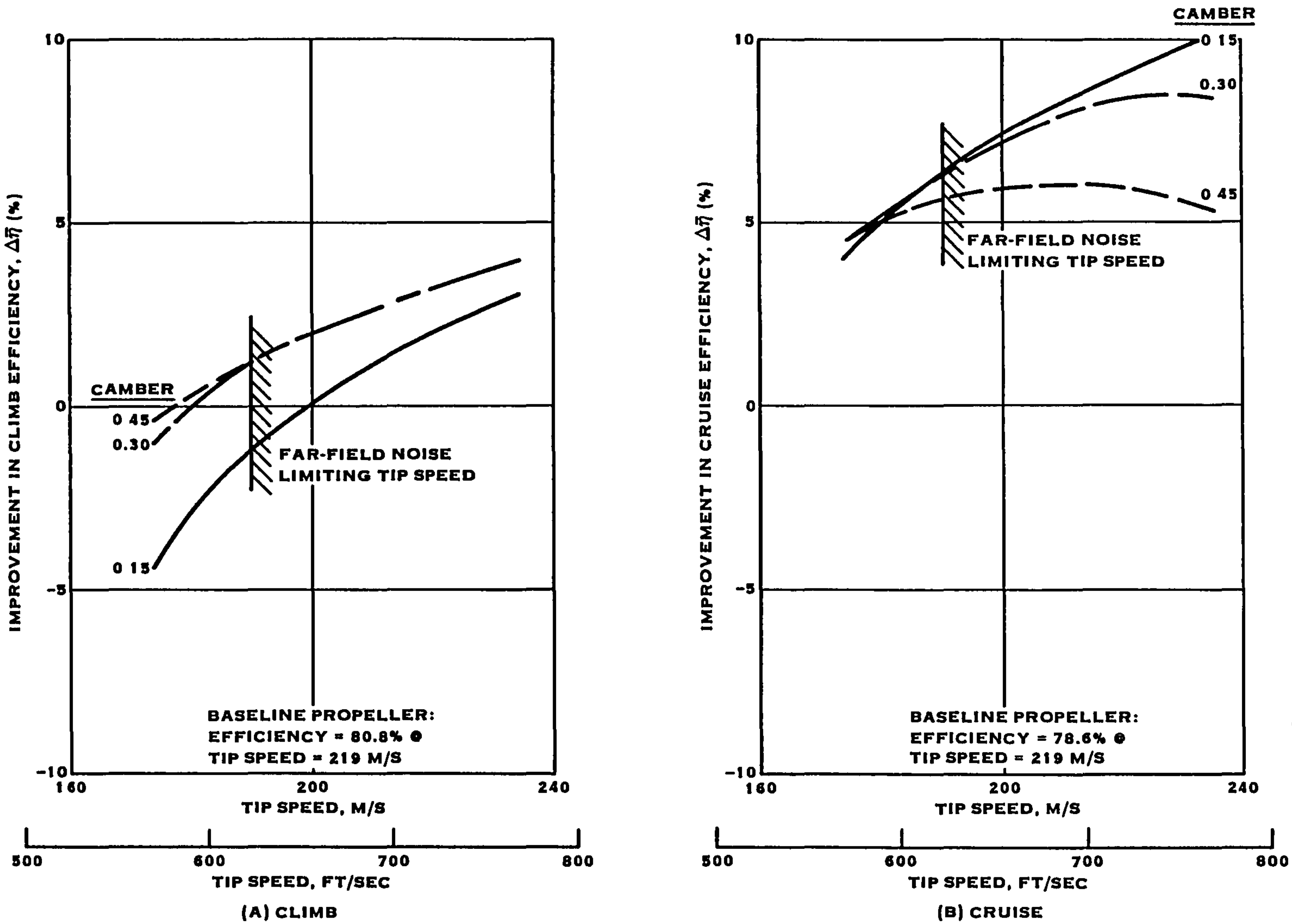

FIGURE 11. EFFECT OF CAMBER AND TIP SPEED ON PROPELLER EFFICIENCY; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP =45°, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 1200, ADVANCED AIRFOILS

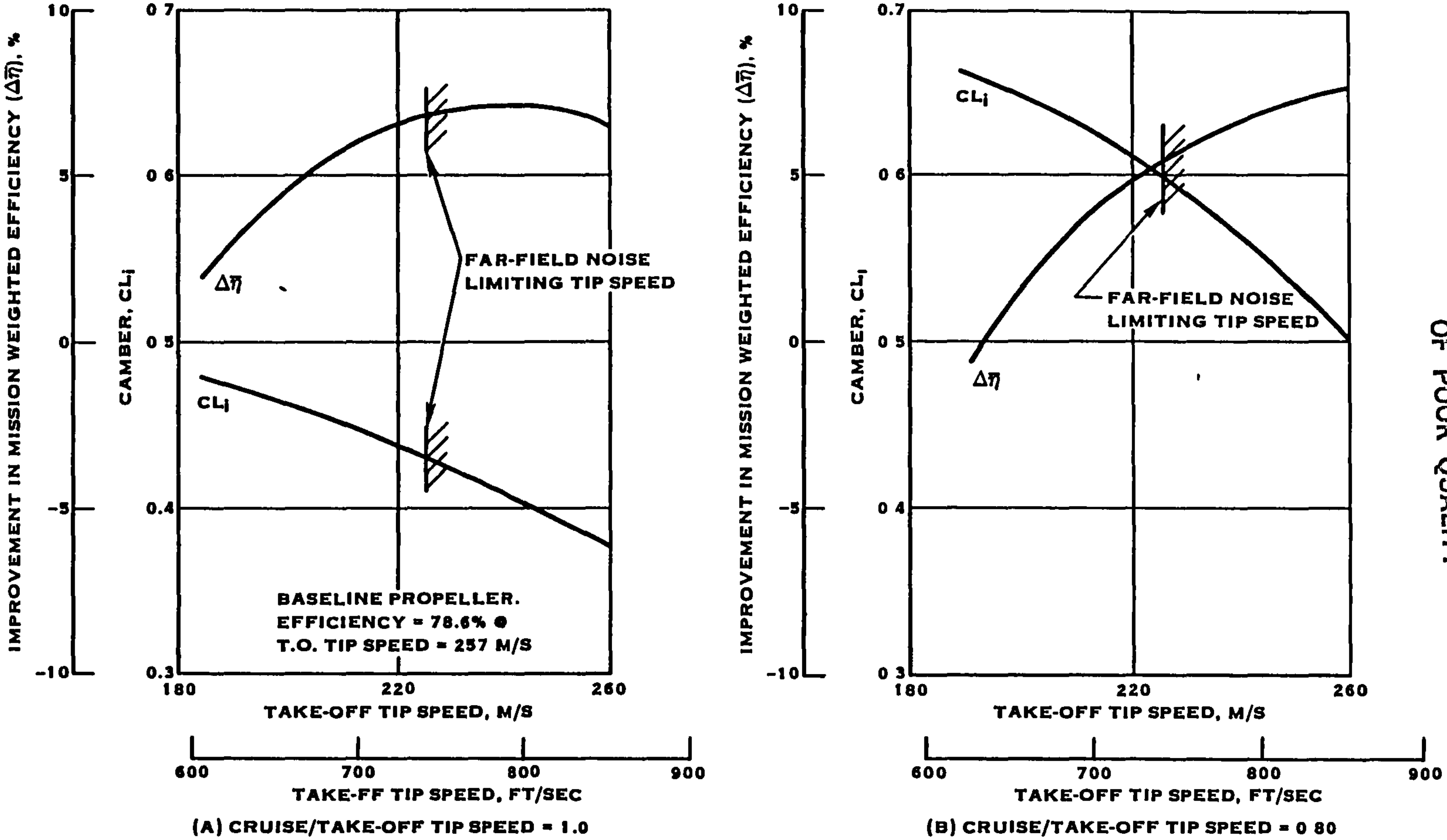

FIGURE 12. EFFECT OF TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY AND OPTIMUM CAMBER; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 420, ADVANCED AIRFOILS, IMPROVED ROOTS

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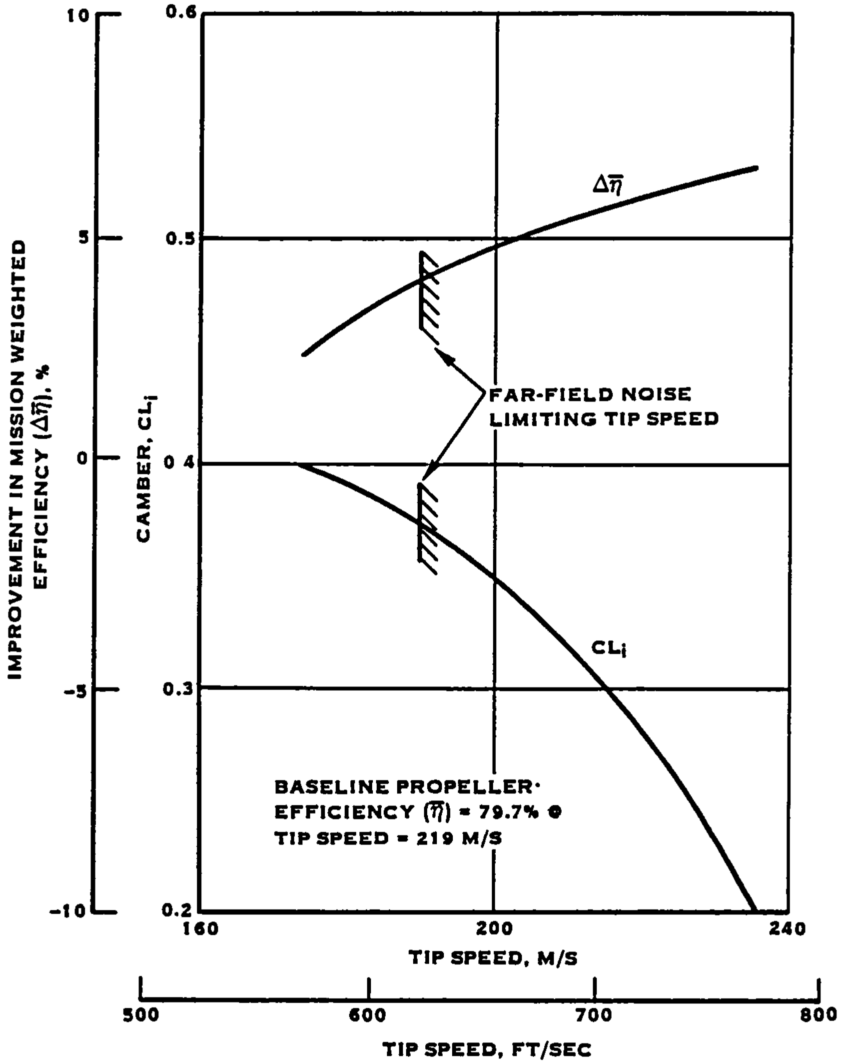


FIGURE 13. EFFECT OF TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY AND OPTIMUM CAMBER; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP = 45°, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 1200, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

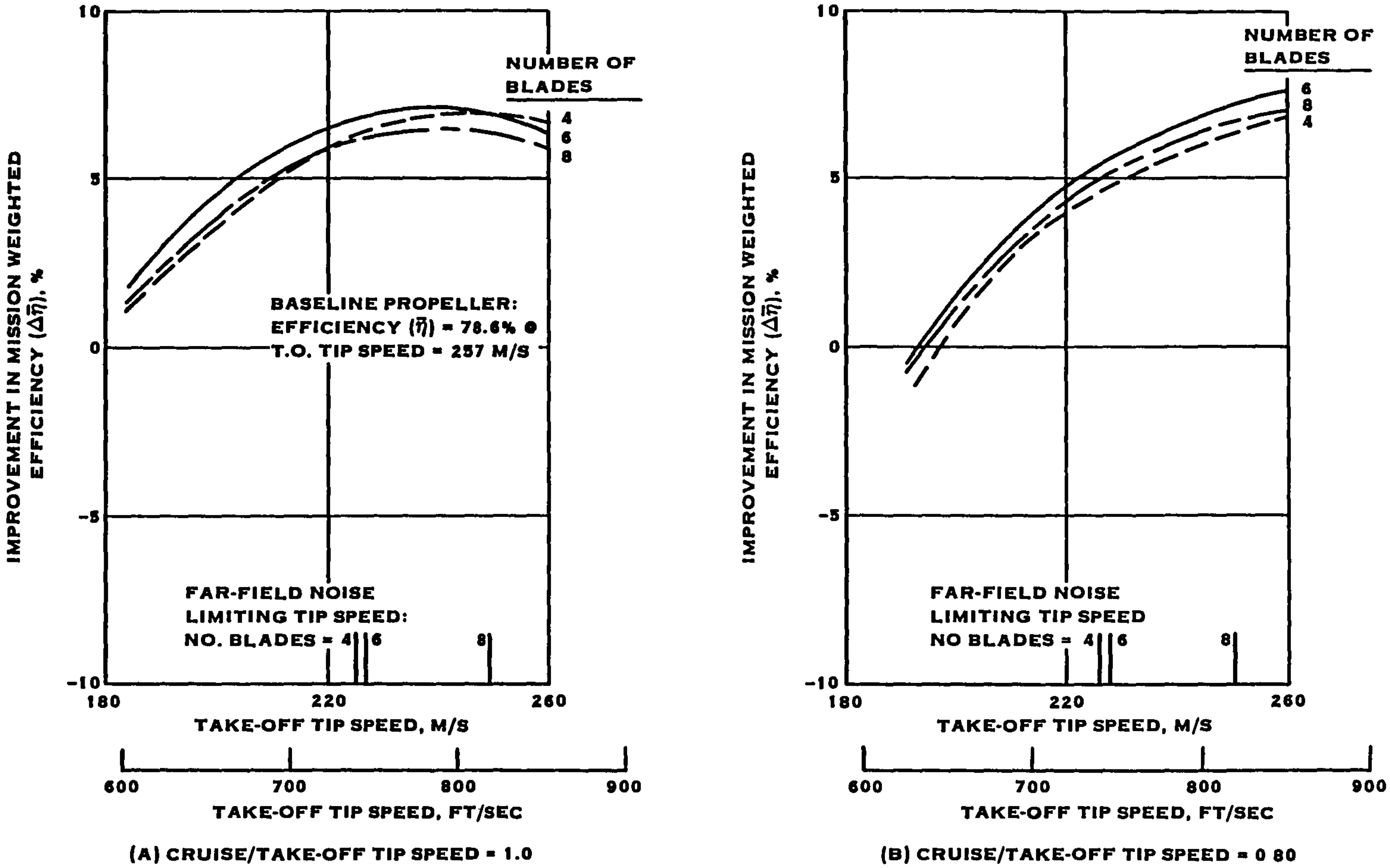


FIGURE 14. EFFECT OF NUMBER OF BLADES AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, OPTIMUM CAMBER, TOTAL ACTIVITY FACTOR = 420, ADVANCED AIRFOILS, IMPROVED ROOTS

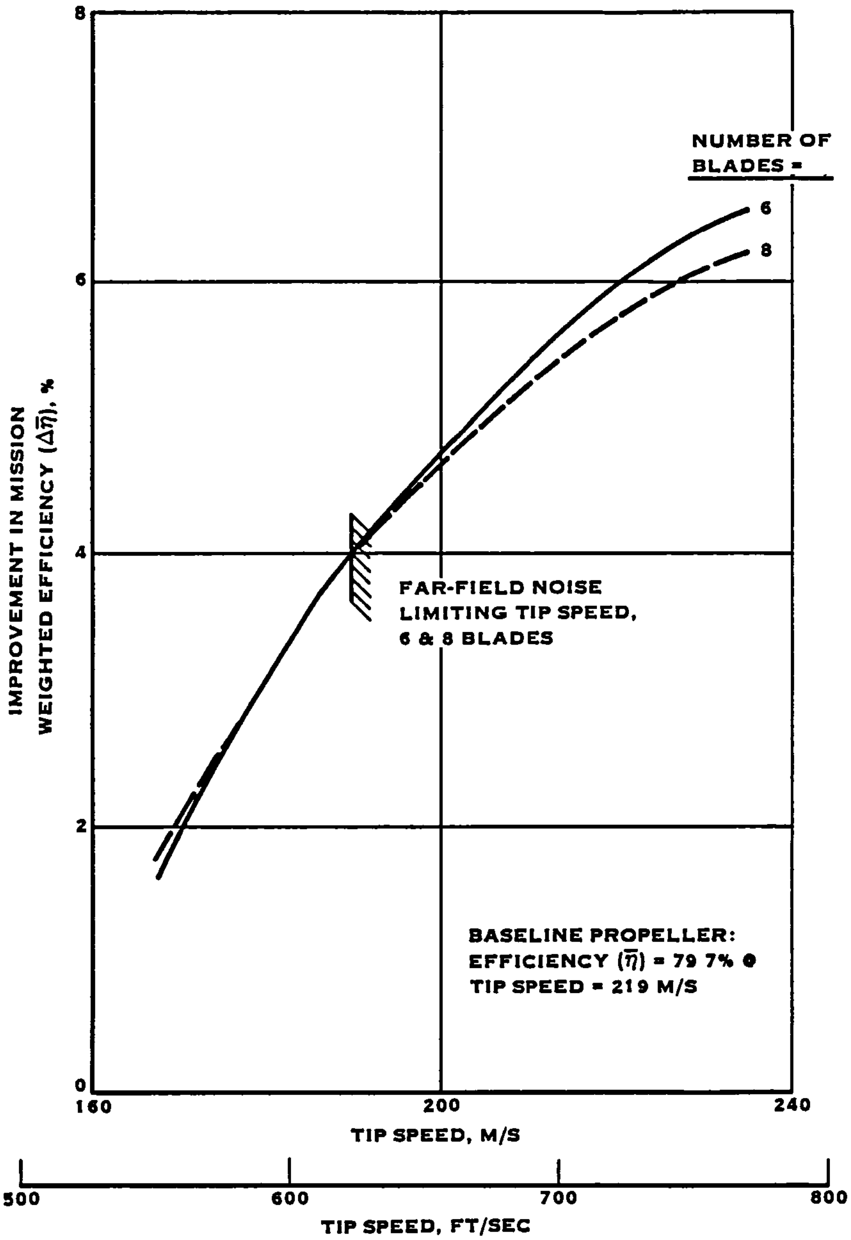


FIGURE 15. EFFECT OF BLADE NUMBER AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP = 45°, OPTIMUM CAMBER, TOTAL ACTIVITY FACTOR = 1200; ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

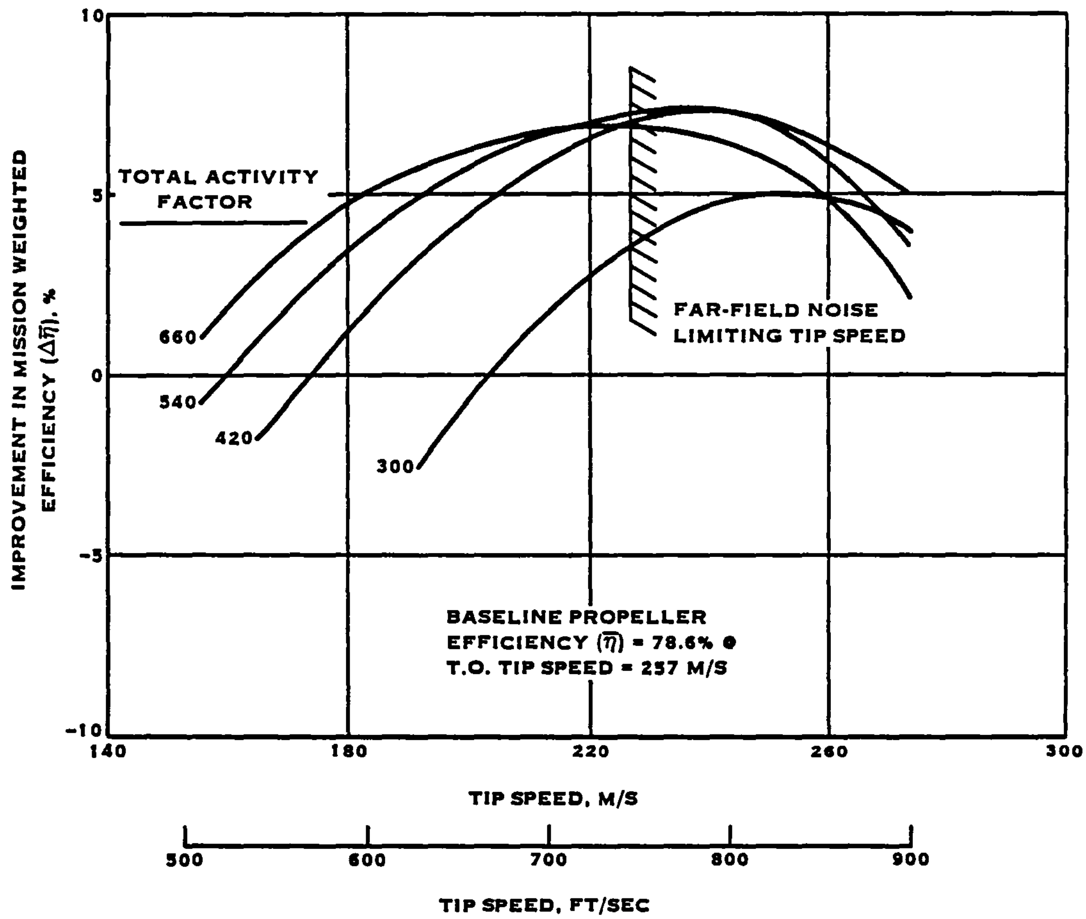


FIGURE 16. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; CRUISE = TAKE-OFF TIP SPEED

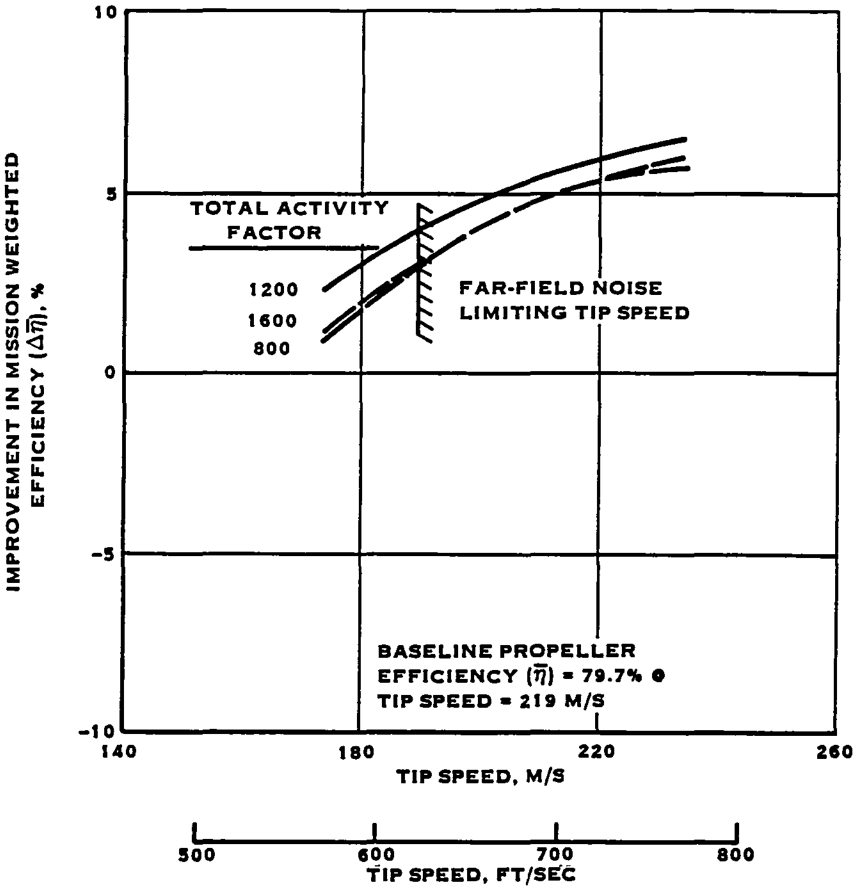


FIGURE 17. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP = 45°, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, CRUISE = TAKE-OFF TIP SPEED

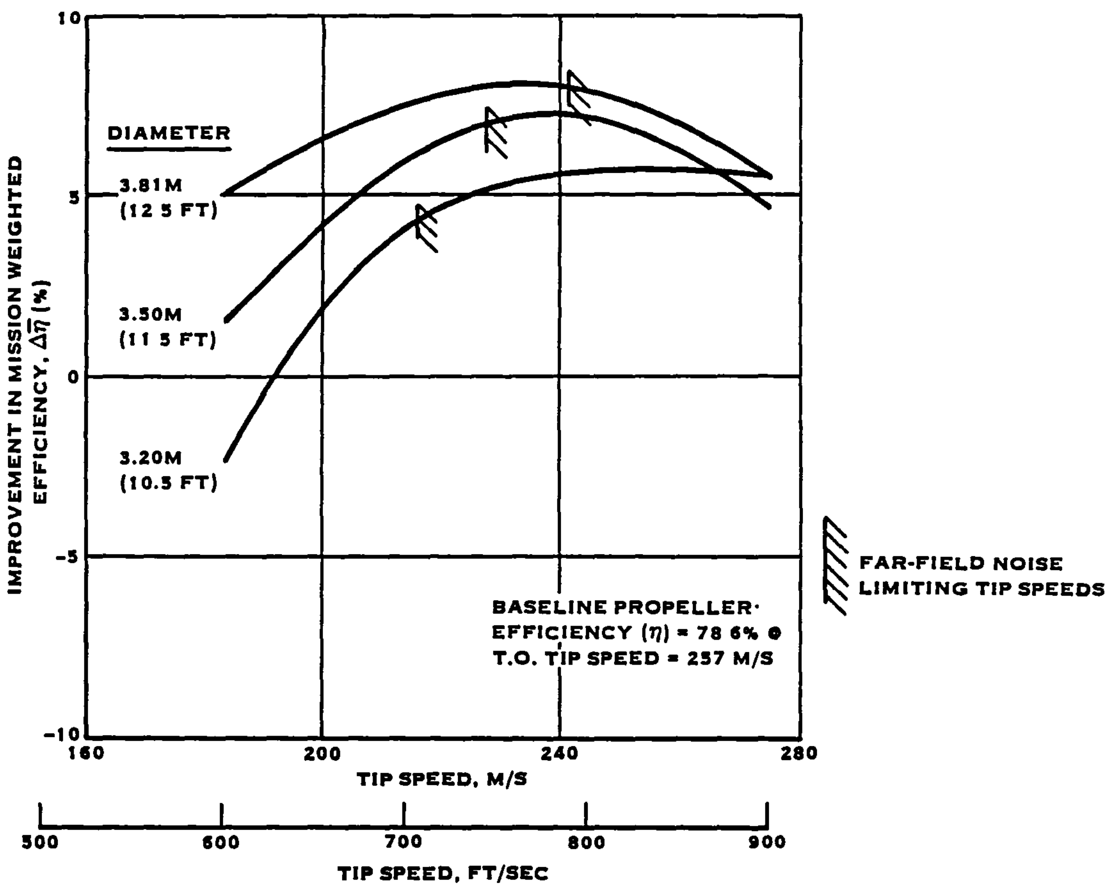


FIGURE 18. EFFECT OF DIAMETER AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION PROPELLER; NO SWEEP OR PROPLETS, OPTIMUM CAMBER, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 420, ADVANCED AIRFOILS, IMPROVED ROOTS; CRUISE = TAKE-OFF TIP SPEED

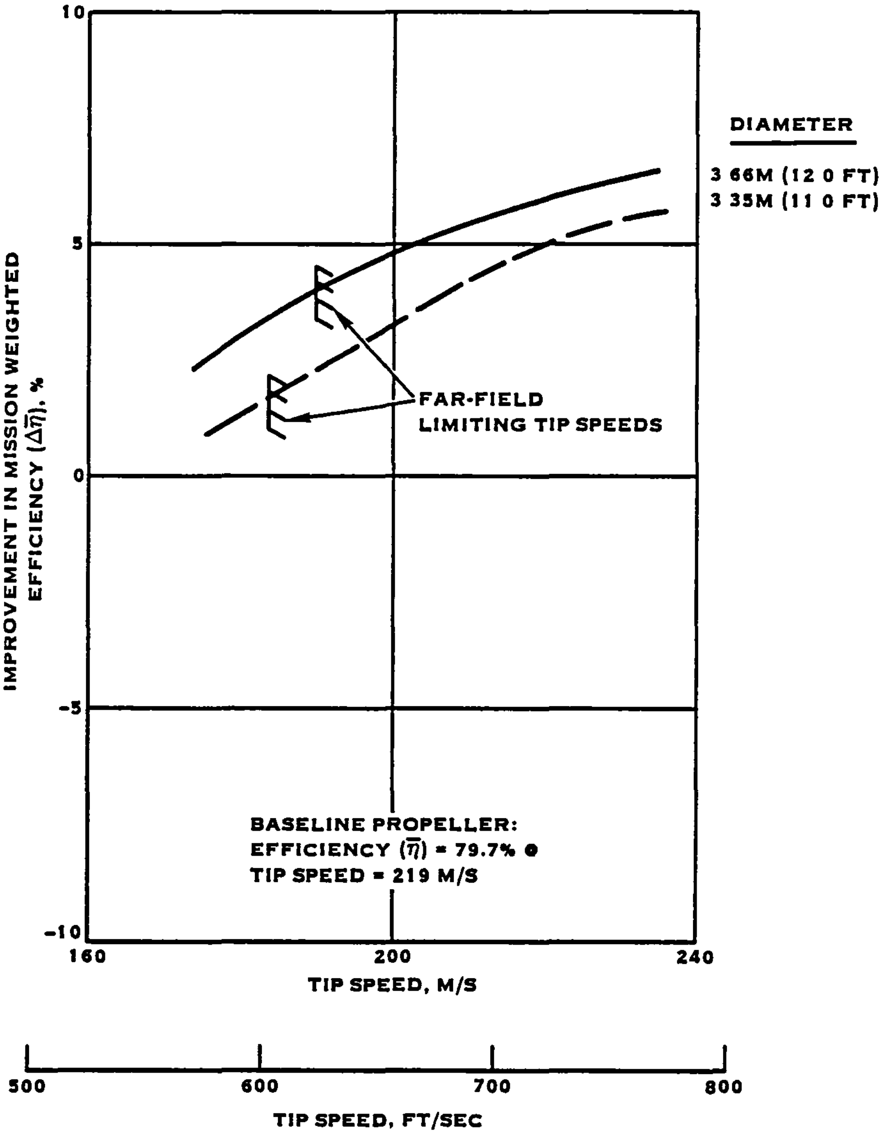
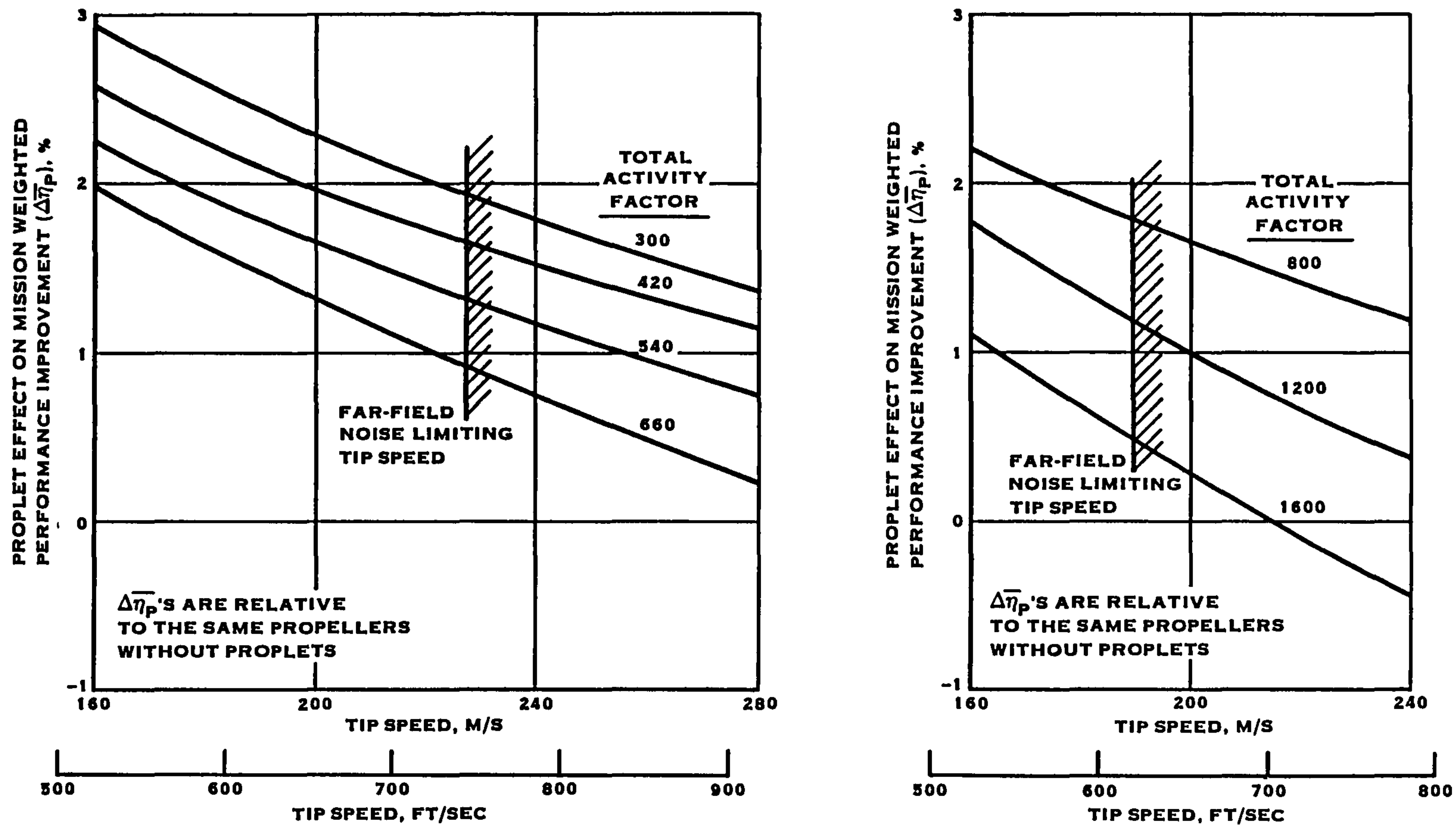


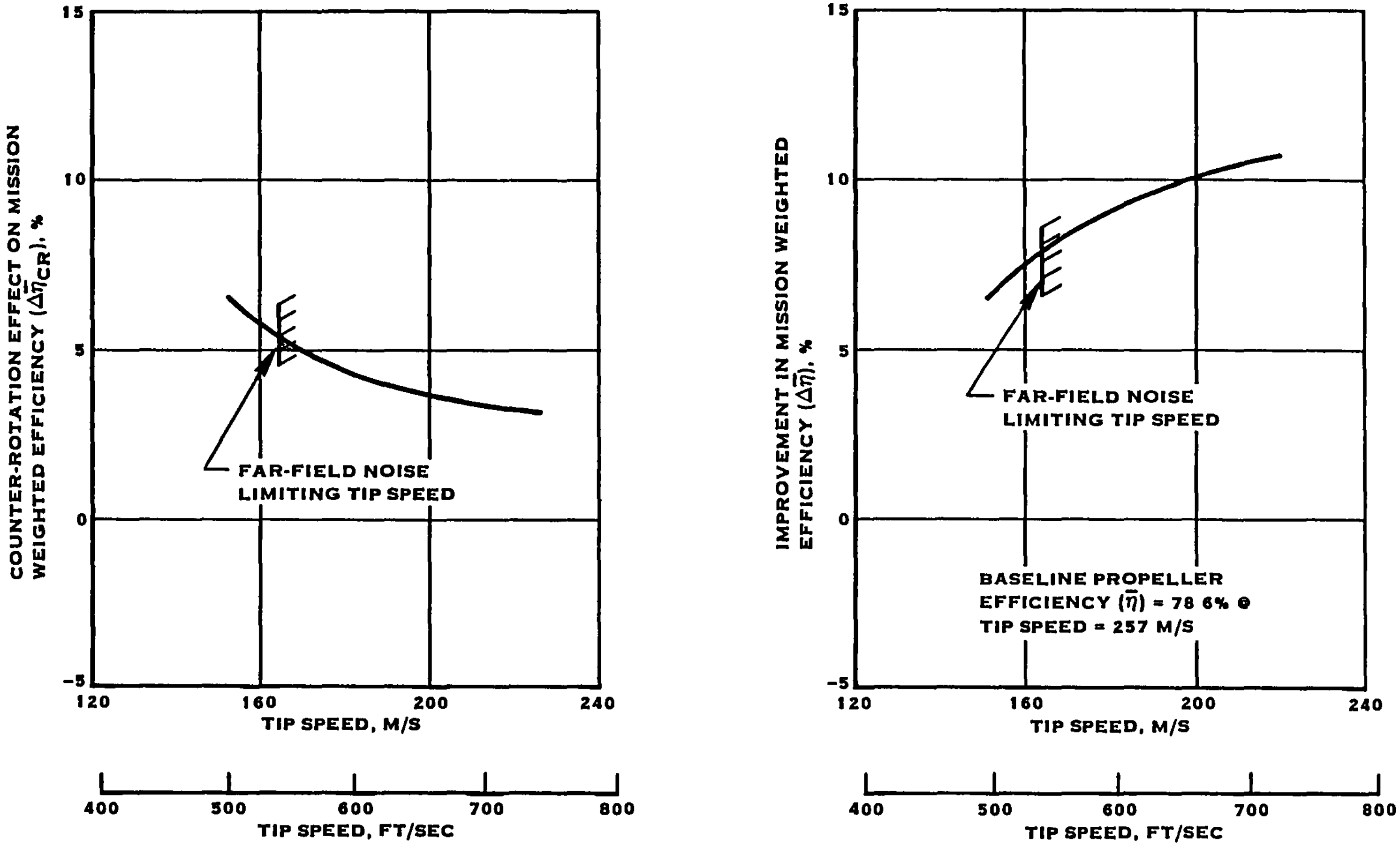
FIGURE 19. EFFECT OF DIAMETER AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION PROPELLER; NO PROPLETS, TIP SWEEP = 45°, OPTIMUM CAMBER, NUMBER OF BLADES = 6, TOTAL ACTIVITY FACTOR = 1200, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED



(A) CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE AND COUNTER-ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; WITH OR WITHOUT SWEEP, NUMBER OF BLADES = 6

(B) LOCKHEED 50 PAX, 0 70 MACH AIRPLANE; SINGLE AND COUNTER-ROTATION, 3 66M (12 0 FT) DIAMETER PROPELLER, WITH OR WITHOUT SWEEP, NUMBER OF BLADES = 6

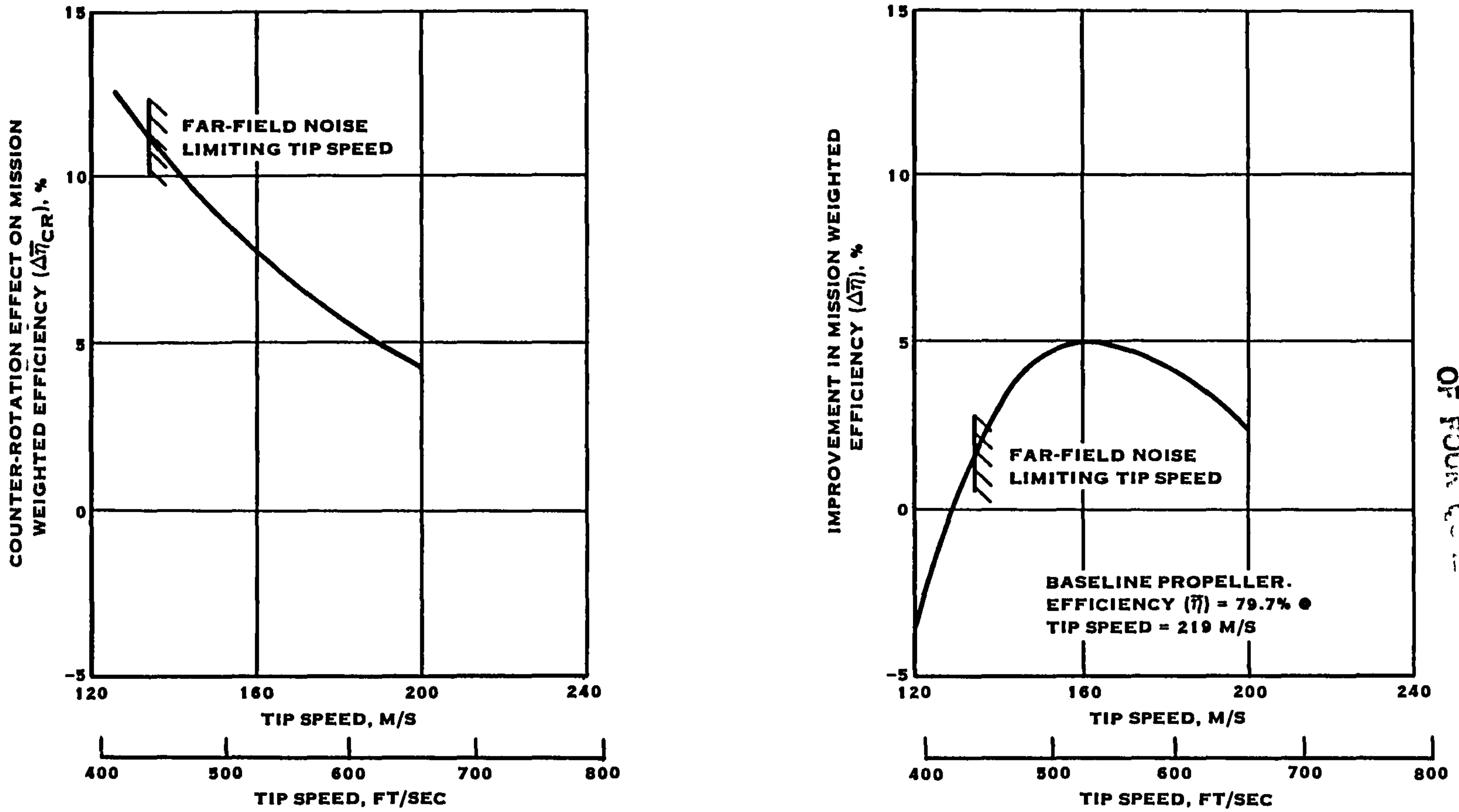
FIGURE 20. EFFECT OF PROPLETS, TIP SPEED AND TOTAL ACTIVITY FACTOR ON MISSION WEIGHTED PROPELLER EFFICIENCY; CRUISE = TAKE-OFF TIP SPEED



(A) MISSION WEIGHTED PERFORMANCE IMPROVEMENT DUE TO COUNTER-ROTATION COMPARED WITH SAME 3.50M (11 5 FT) DIAMETER SINGLE ROTATION PROPELLER OPERATING AT THE SAME TIP SPEED

(B) MISSION WEIGHTED PERFORMANCE IMPROVEMENT COMPARED WITH THE BASELINE PROPELLER FOR AN 8-BLADED COUNTER-ROTATION, 3 50M (11 5 FT) DIAMETER PROPELLER, NO SWEEP OR PROPLETS, OPTIMUM CAMBER, TOTAL ACTIVITY FACTOR = 660, ADVANCED AIRFOILS, IMPROVED ROOTS

FIGURE 21. EFFECT OF COUNTER-ROTATION AND TIP SPEED ON MISSION WEIGHTED EFFICIENCY FOR THE CONVAIR 30 PAX, 0.47 MACH AIRPLANE; CRUISE = TAKE-OFF TIP SPEED



(A) MISSION WEIGHTED PERFORMANCE IMPROVEMENT DUE TO COUNTER-ROTATION COMPARED WITH SAME 3.66M (12.0 FT) DIAMETER SINGLE ROTATION PROPELLER OPERATING AT THE SAME TIP SPEED

(B) MISSION WEIGHTED PERFORMANCE IMPROVEMENT COMPARED WITH THE BASELINE PROPELLER FOR AN 8-BLADED COUNTER-ROTATION, 3.66M (12 0 FT) DIAMETER PROPELLER, NO SWEEP OR PROPLETS, OPTIMUM CAMBER, TOTAL ACTIVITY FACTOR = 1840, ADVANCED AIRFOILS

FIGURE 22. EFFECT OF COUNTER-ROTATION AND TIP SPEED ON MISSION WEIGHTED EFFICIENCY FOR THE LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; CRUISE = TAKE-OFF TIP SPEED

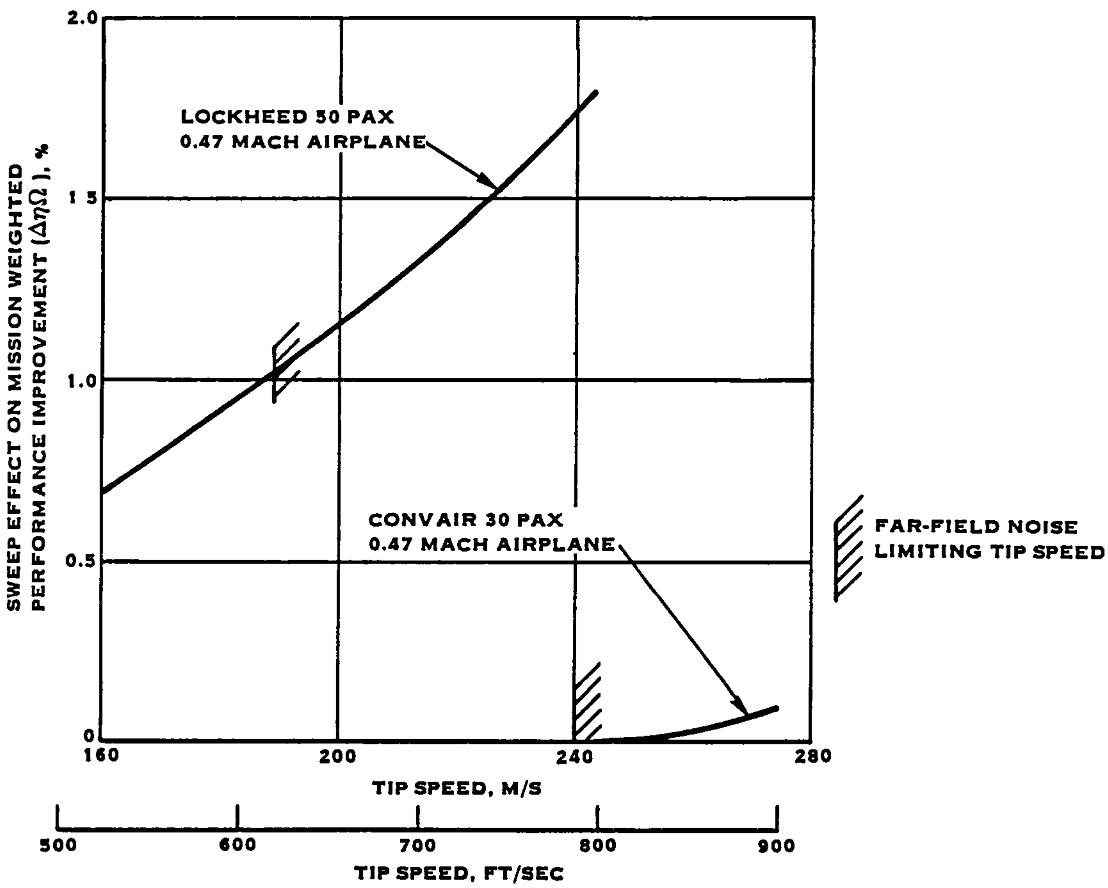


FIGURE 23. EFFECT OF 45° OF TIP SWEEP AND TIP SPEED ON MISSION WEIGHTED PROPELLER EFFICIENCY COMPARED WITH THE SAME PROPELLERS WITHOUT SWEEP; EQUAL CRUISE AND TAKE-OFF SPEEDS

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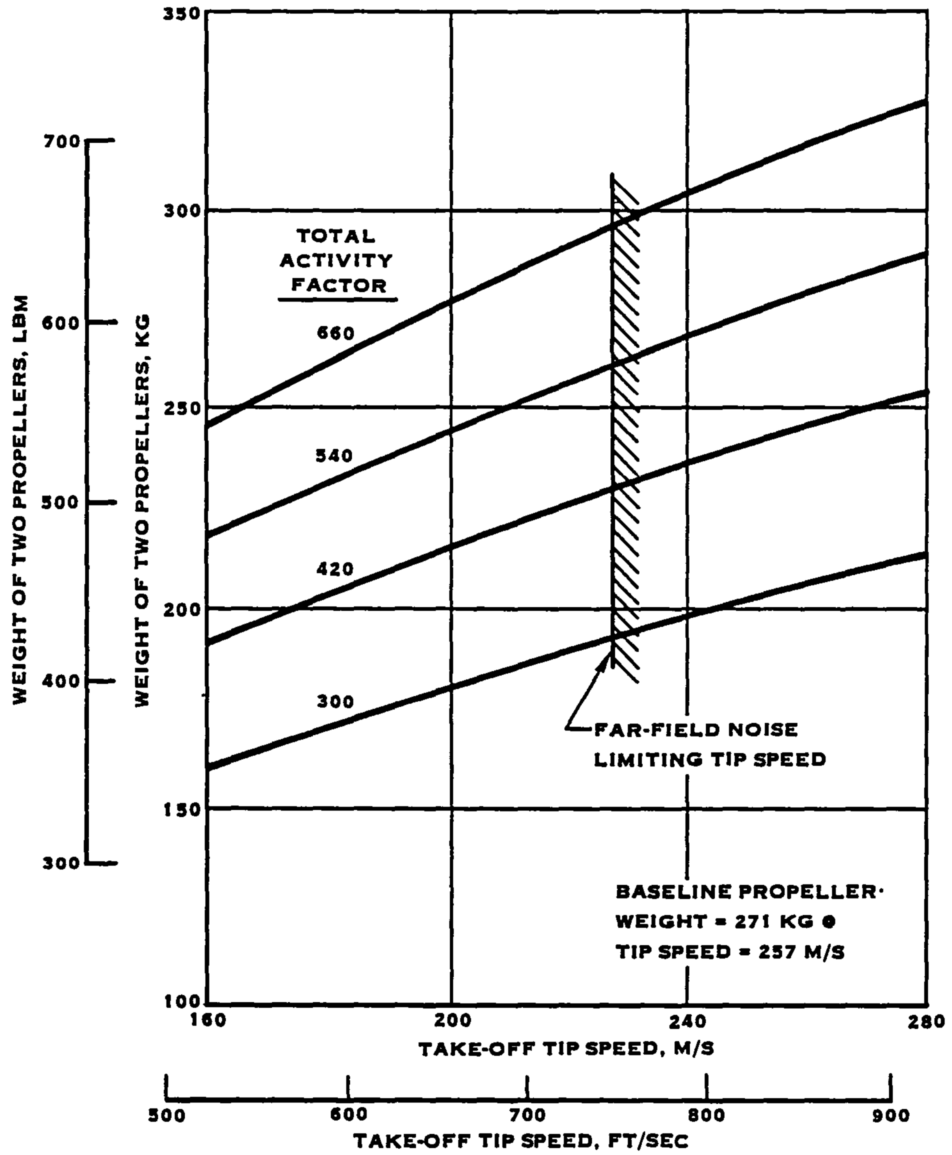

FIGURE 24. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON PROPELLER WEIGHT; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLERS; NO SWEEP OR PROPLETS, ADVANCED COMPOSITE MATERIAL, NUMBER OF BLADES = 6

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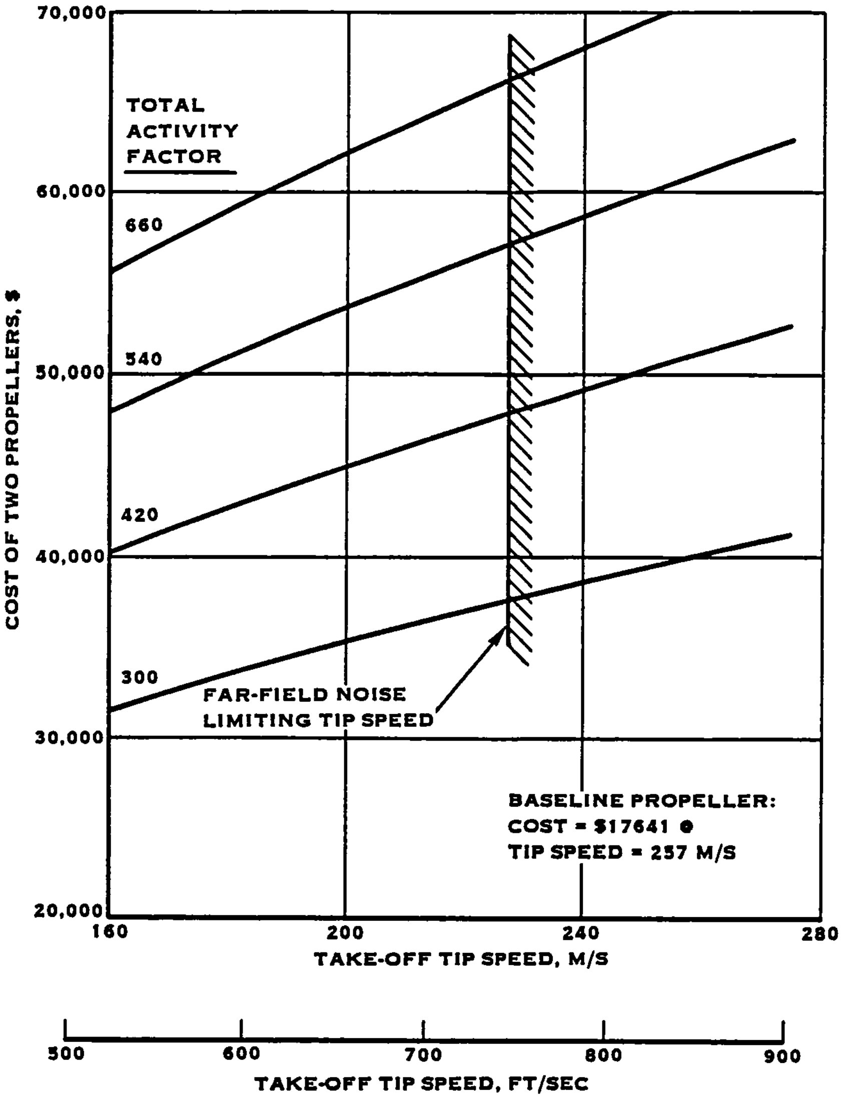

FIGURE 25. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON PROPELLER COST; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER, SINGLE ROTATION PROPELLERS; NO SWEEP OR PROPLETS, ADVANCED MATERIALS, NO ADVANCED PRECISION SYNCHROPHASER, NUMBER OF BLADES = 6

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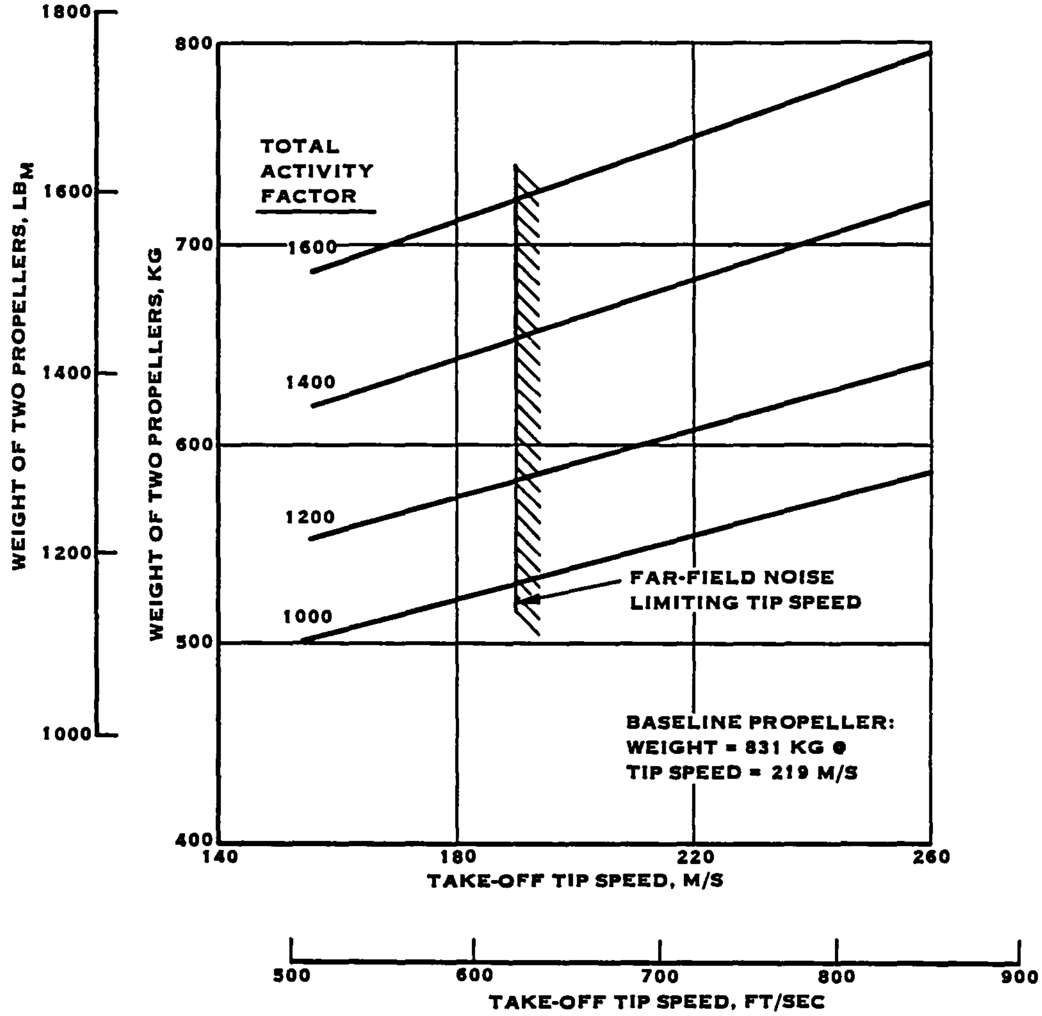

FIGURE 26. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON PROPELLER WEIGHT; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLERS; NO PROPLETS, TIP SWEEP = 45°, NUMBER OF BLADES = 6, ADVANCED COMPOSITE MATERIAL

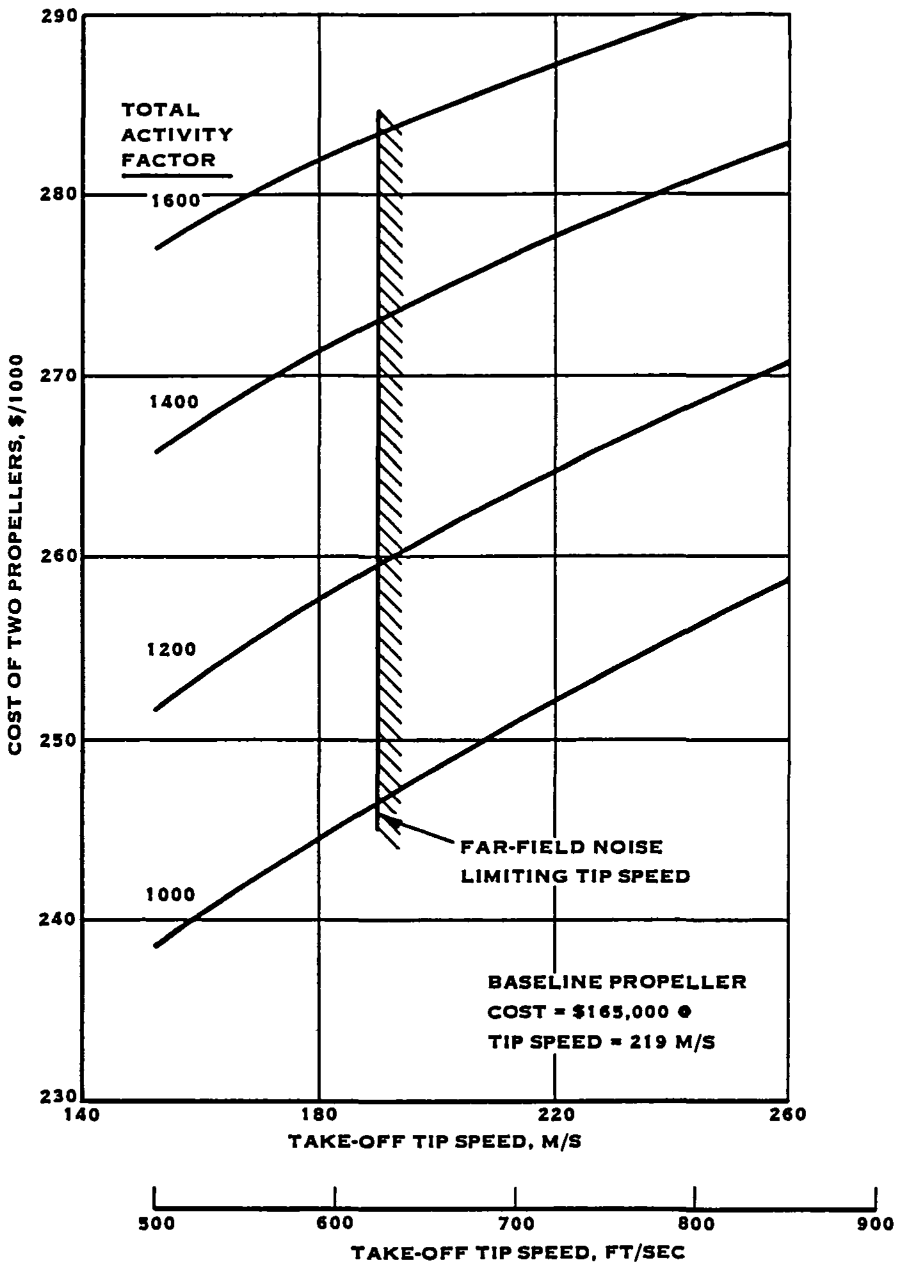

FIGURE 27. EFFECT OF TOTAL ACTIVITY FACTOR AND TIP SPEED ON PROPELLER COST; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLERS; NO PROPLETS, TIP SWEEP = 45°, NUMBER OF BLADES = 6, ADVANCED COMPOSITE MATERIAL, NO ADVANCED PRECISION SYNCHROPHASER

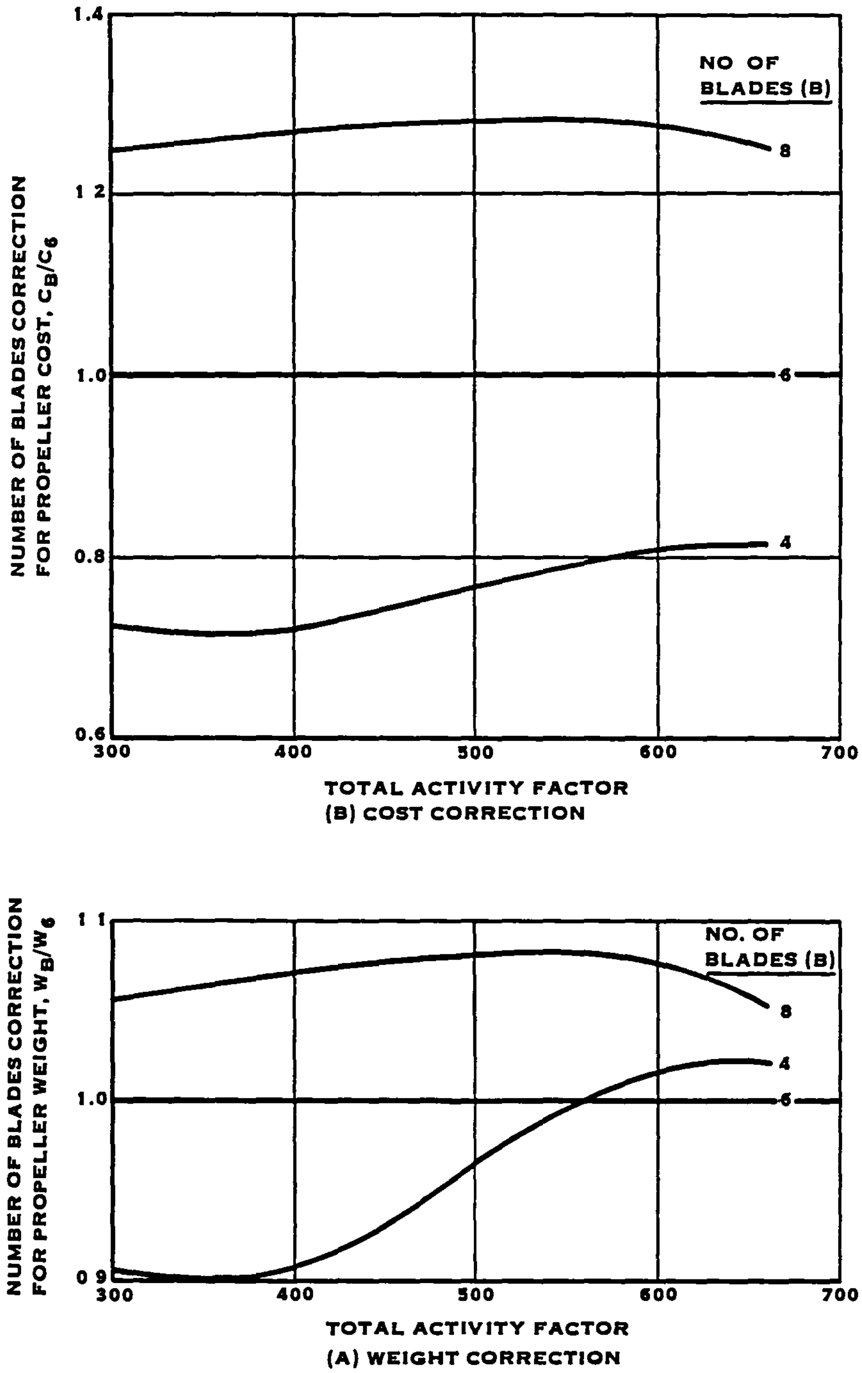

FIGURE 28. EFFECT OF NUMBER OF BLADES AND TOTAL ACTIVITY FACTOR ON PROPELLER WEIGHT AND COST; CONVAIR 30 PAX, 0.47 MACH AIRPLANE

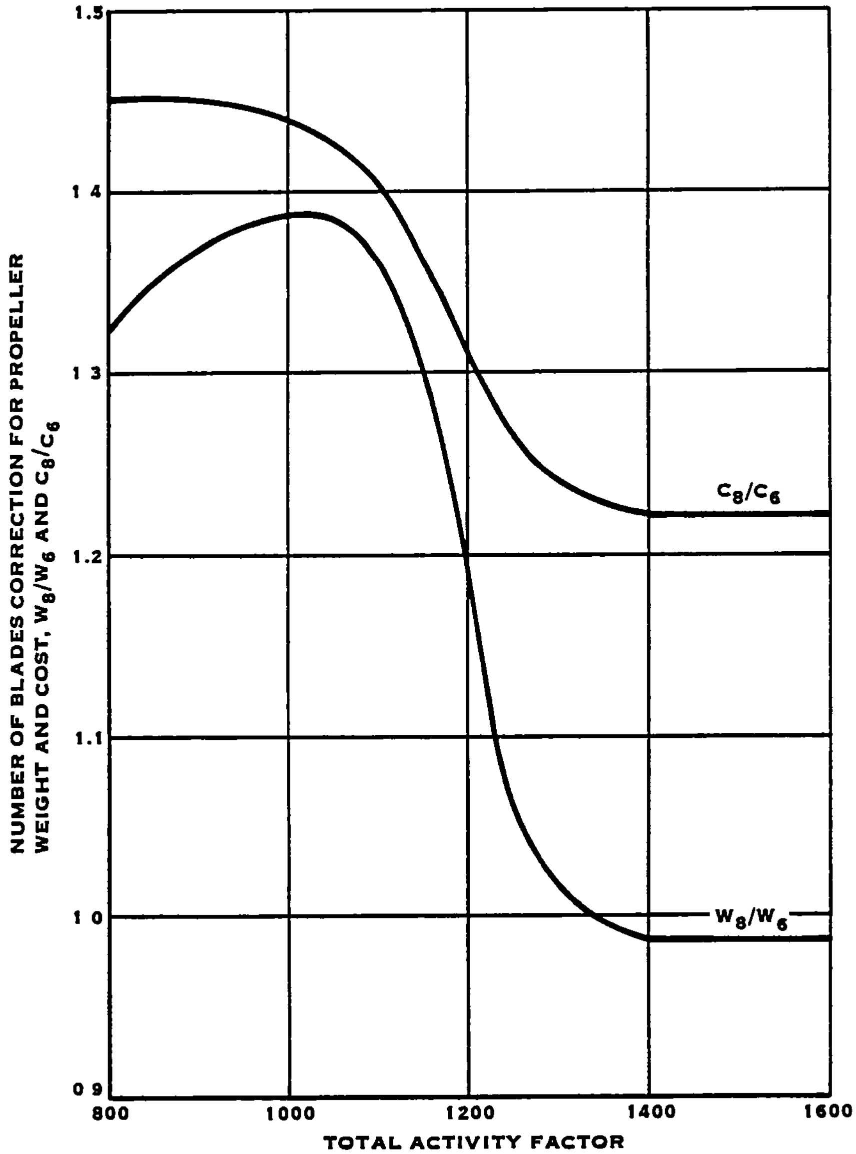

FIGURE 29. EFFECT OF NUMBER OF BLADES AND TOTAL ACTIVITY FACTOR ON PROPELLER WEIGHT AND COST; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE

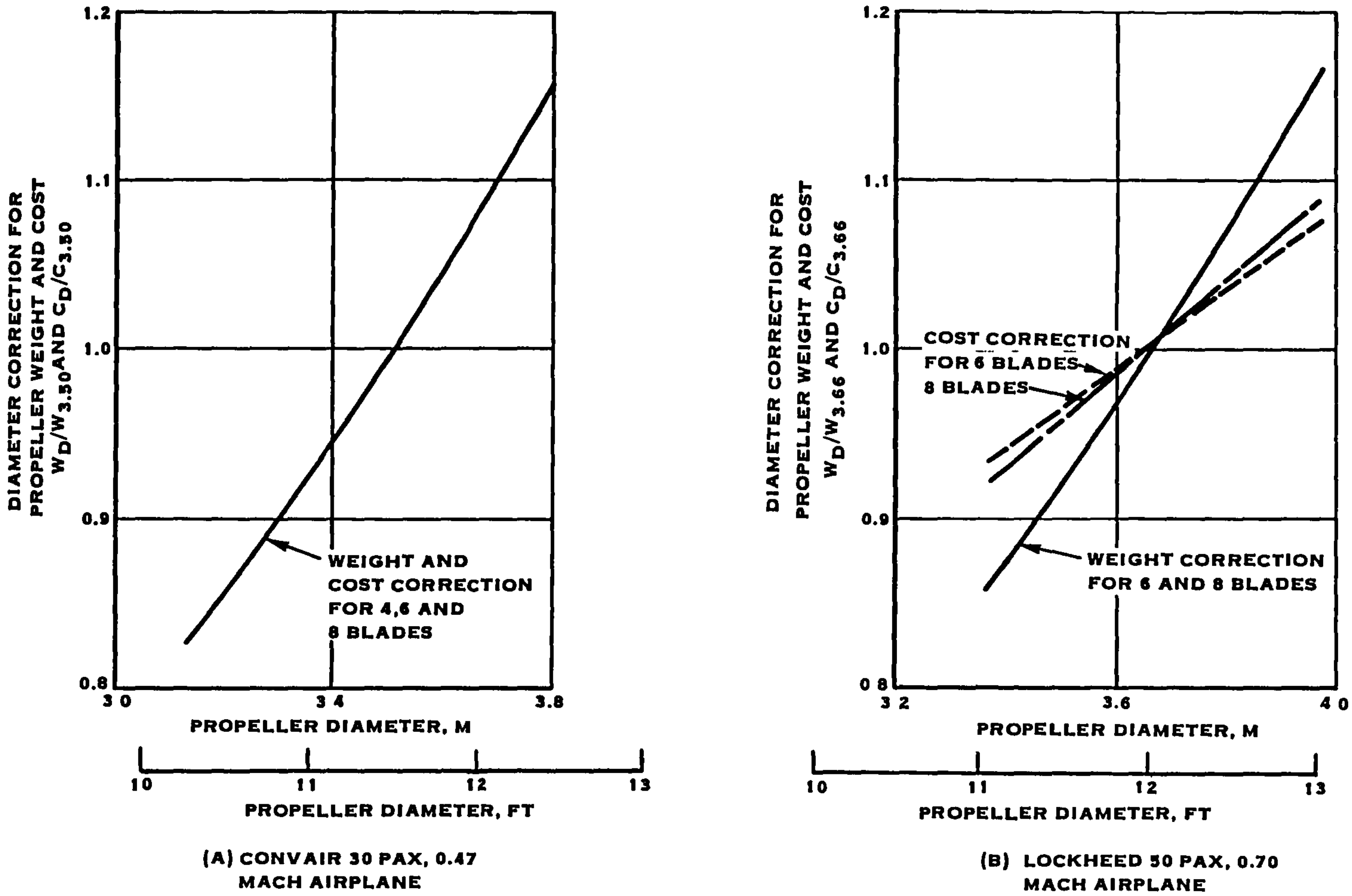

FIGURE 30. EFFECT OF DIAMETER ON PROPELLER WEIGHT AND COST

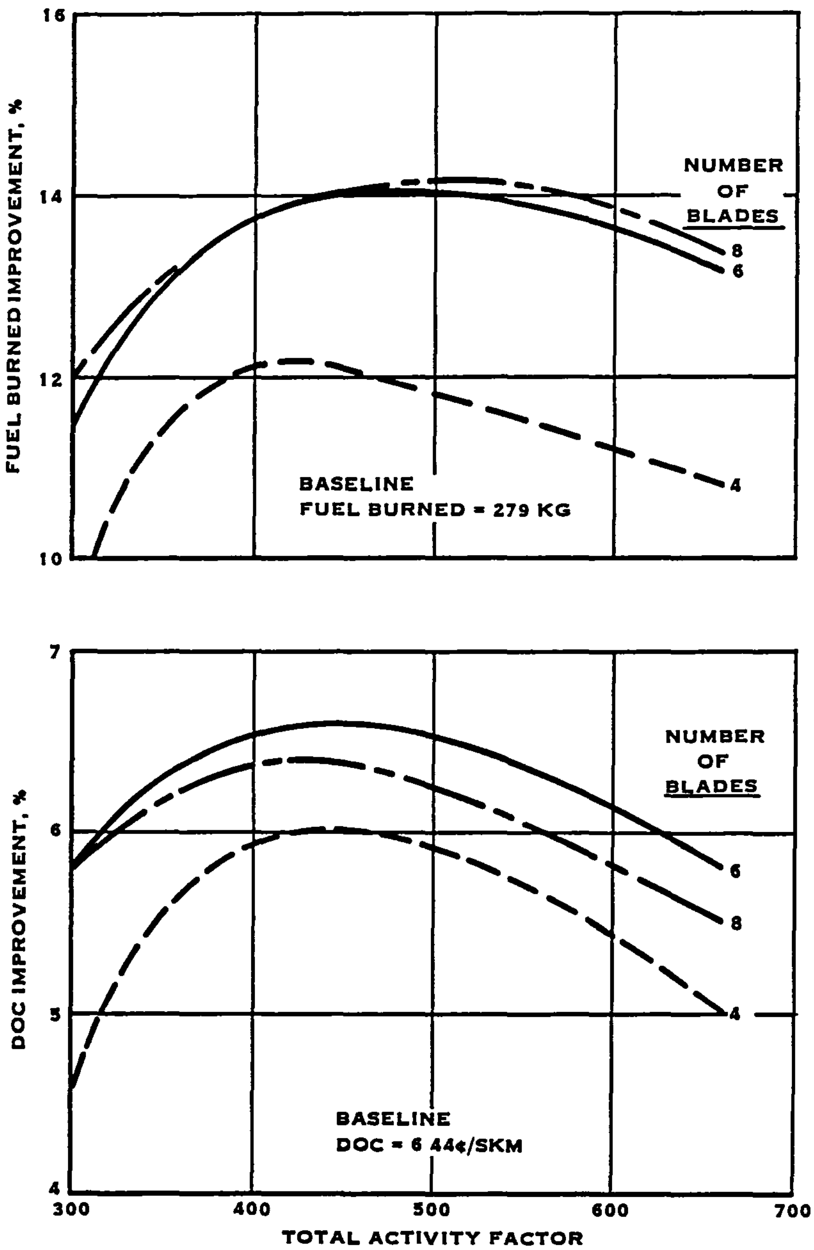

FIGURE 31. EFFECT OF NUMBER OF BLADES AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/ TAKE-OFF TIP SPEED

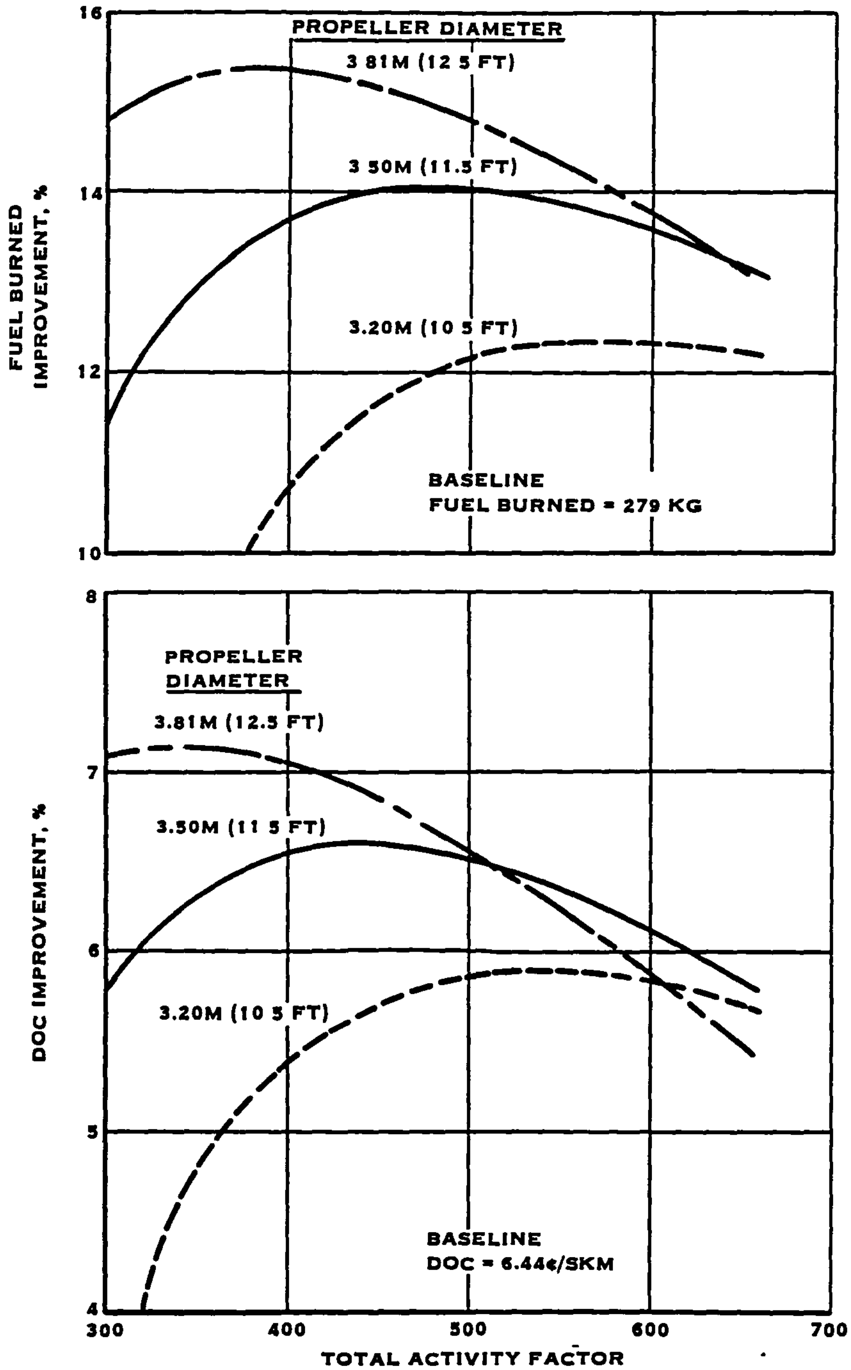

FIGURE 32. EFFECT OF PROPELLER DIAMETER AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION PROPELLER; NO SWEEP OR PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/TAKE-OFF TIP SPEED

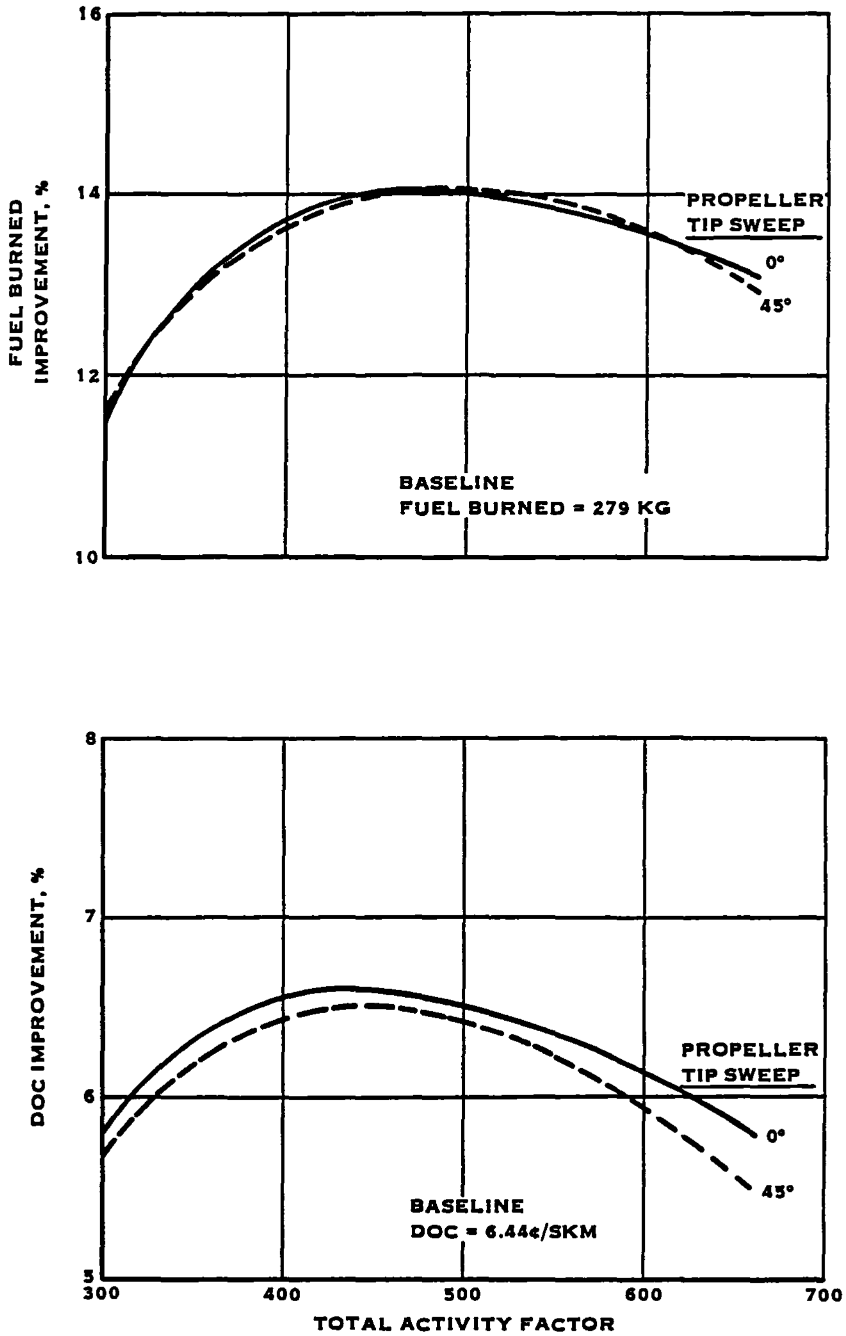

FIGURE 33. EFFECT OF TIP SWEEP AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/ TAKE-OFF TIP SPEED

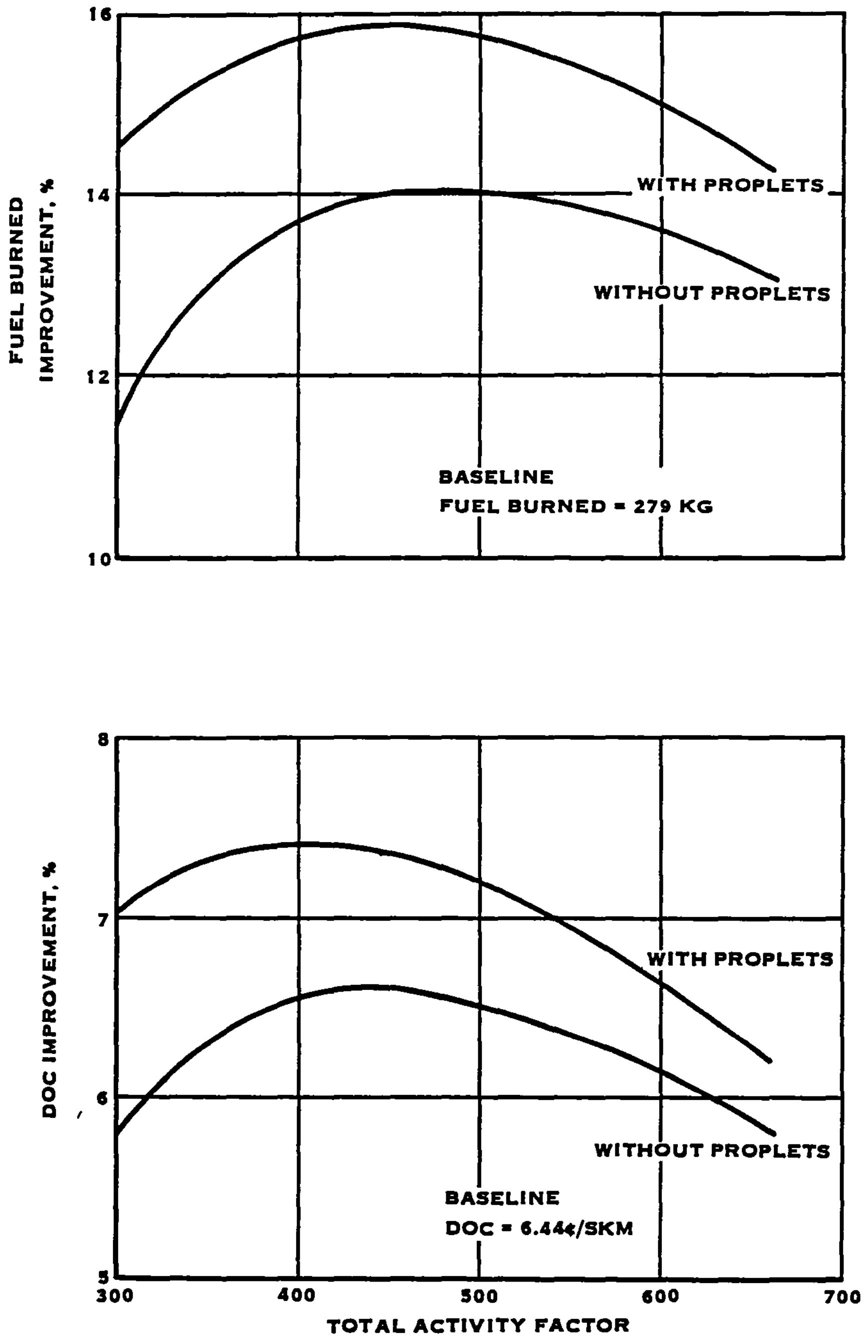

FIGURE 34. EFFECT OF PROPLETS AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/TAKE-OFF TIP SPEED

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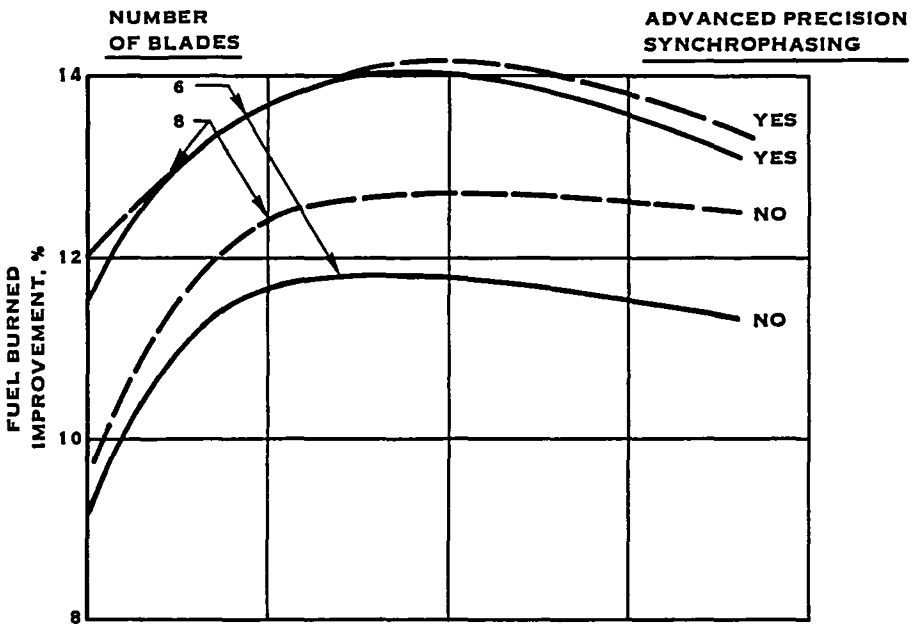

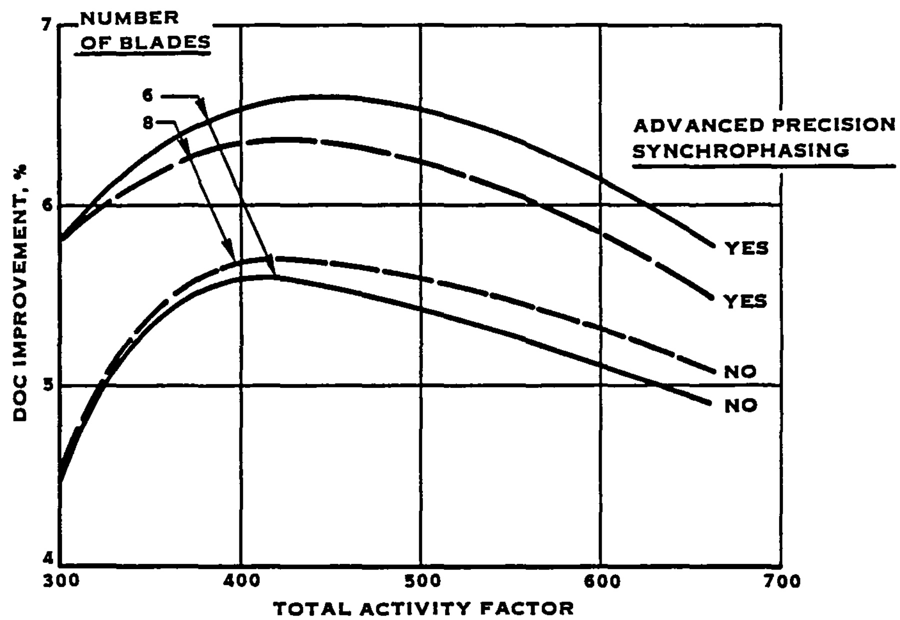

FIGURE 35. EFFECT OF ADVANCED PRECISION SYNCHROPHASING AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ADVANCED COMPOSITE MATERIAL, OPTIMUM CAMBER, NUMBER OF BLADES=6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/TAKE-OFF TIP SPEED

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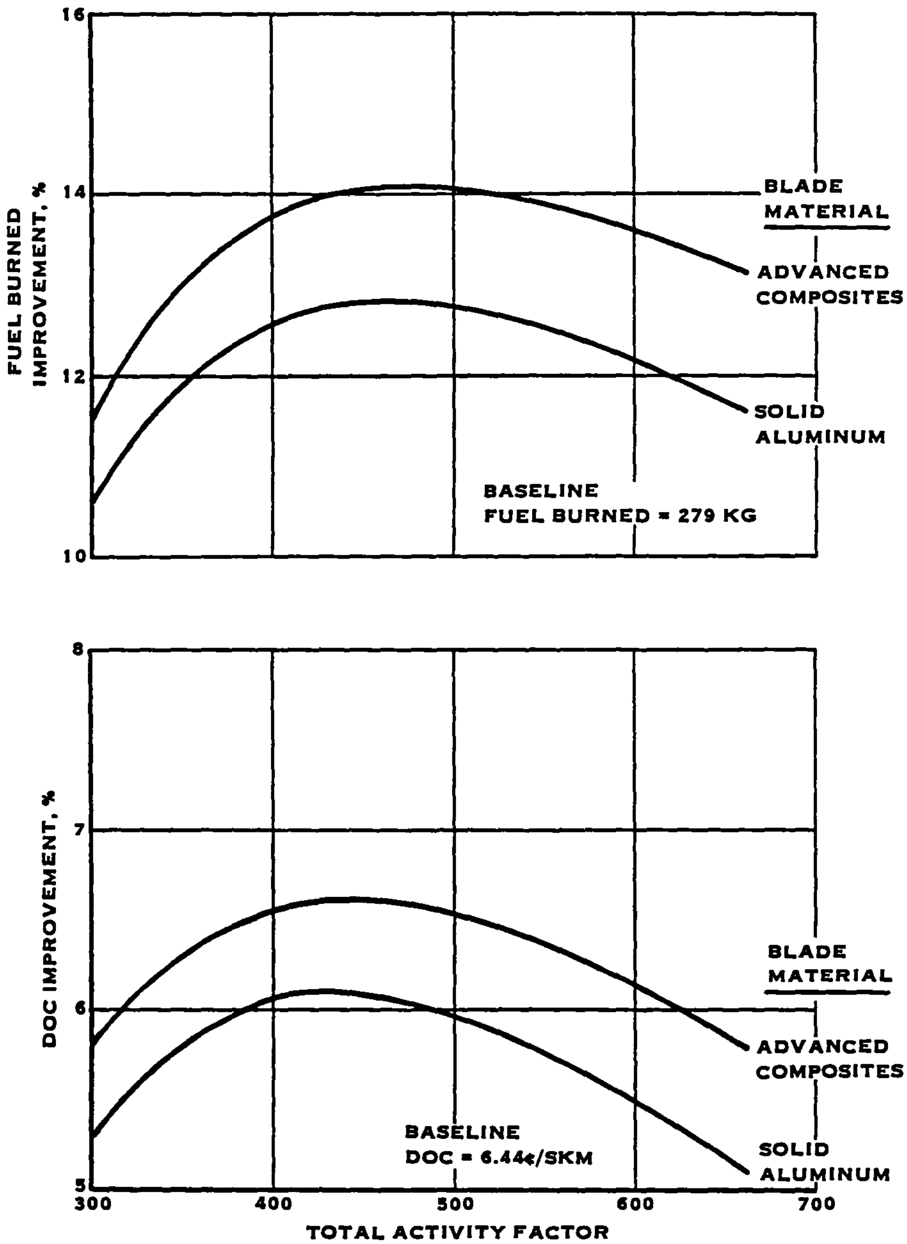

FIGURE 36. EFFECT OF BLADE MATERIAL AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/TAKE-OFF TIP SPEED

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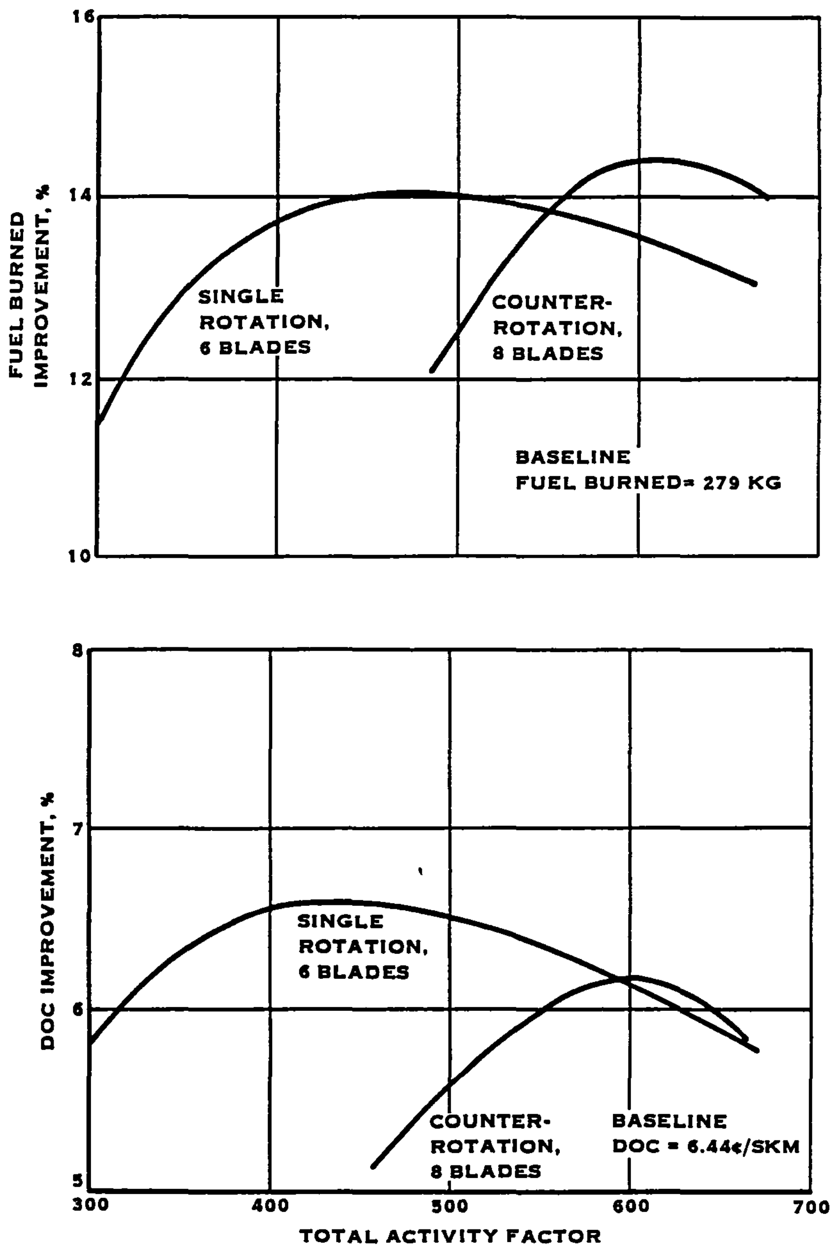

FIGURE 37. EFFECT OF COUNTER-ROTATION AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP OR PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS, IMPROVED ROOTS; OPTIMUM CRUISE/TAKE-OFF TIP SPEED

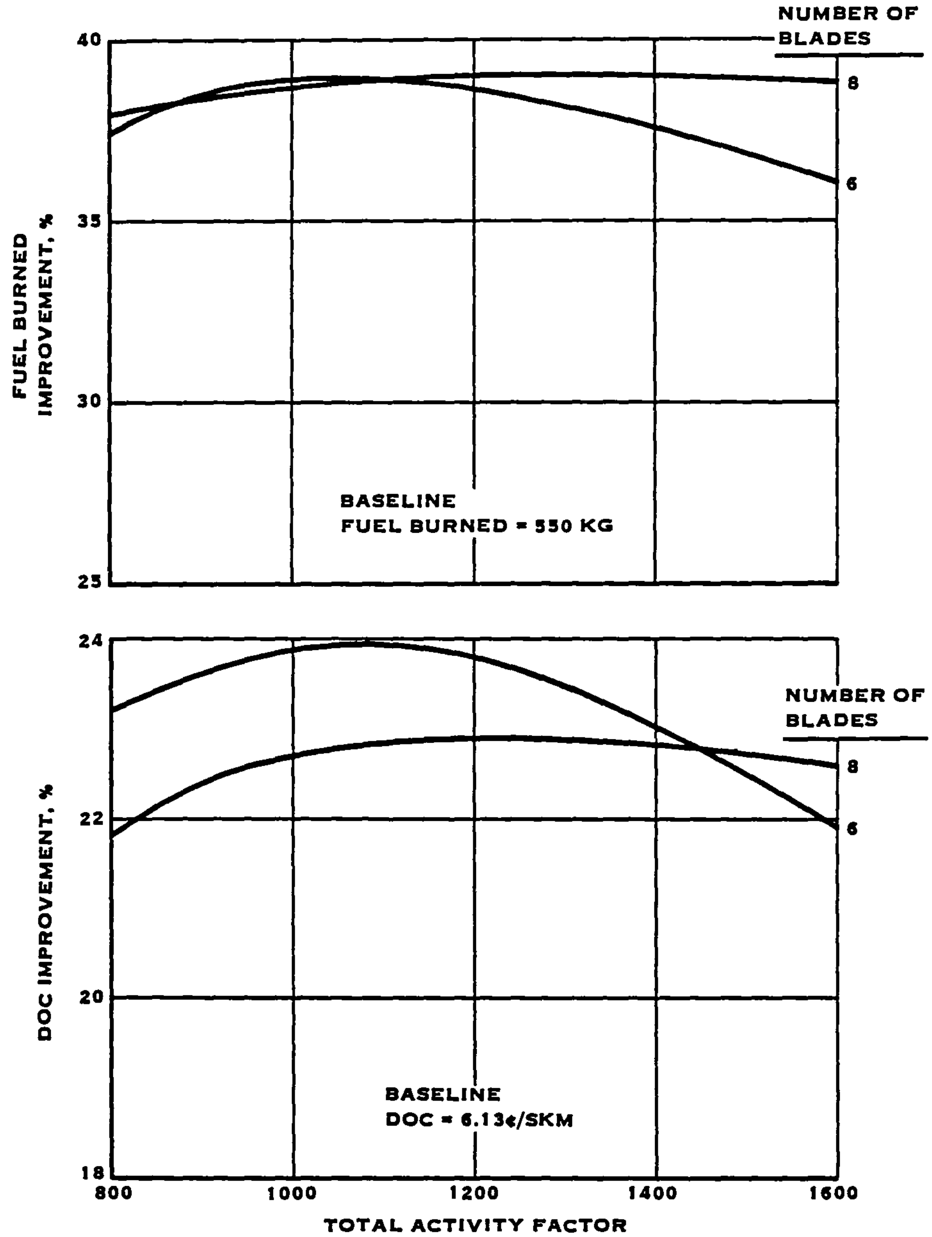

FIGURE 38. EFFECT OF NUMBER OF BLADES AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP = 45°, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

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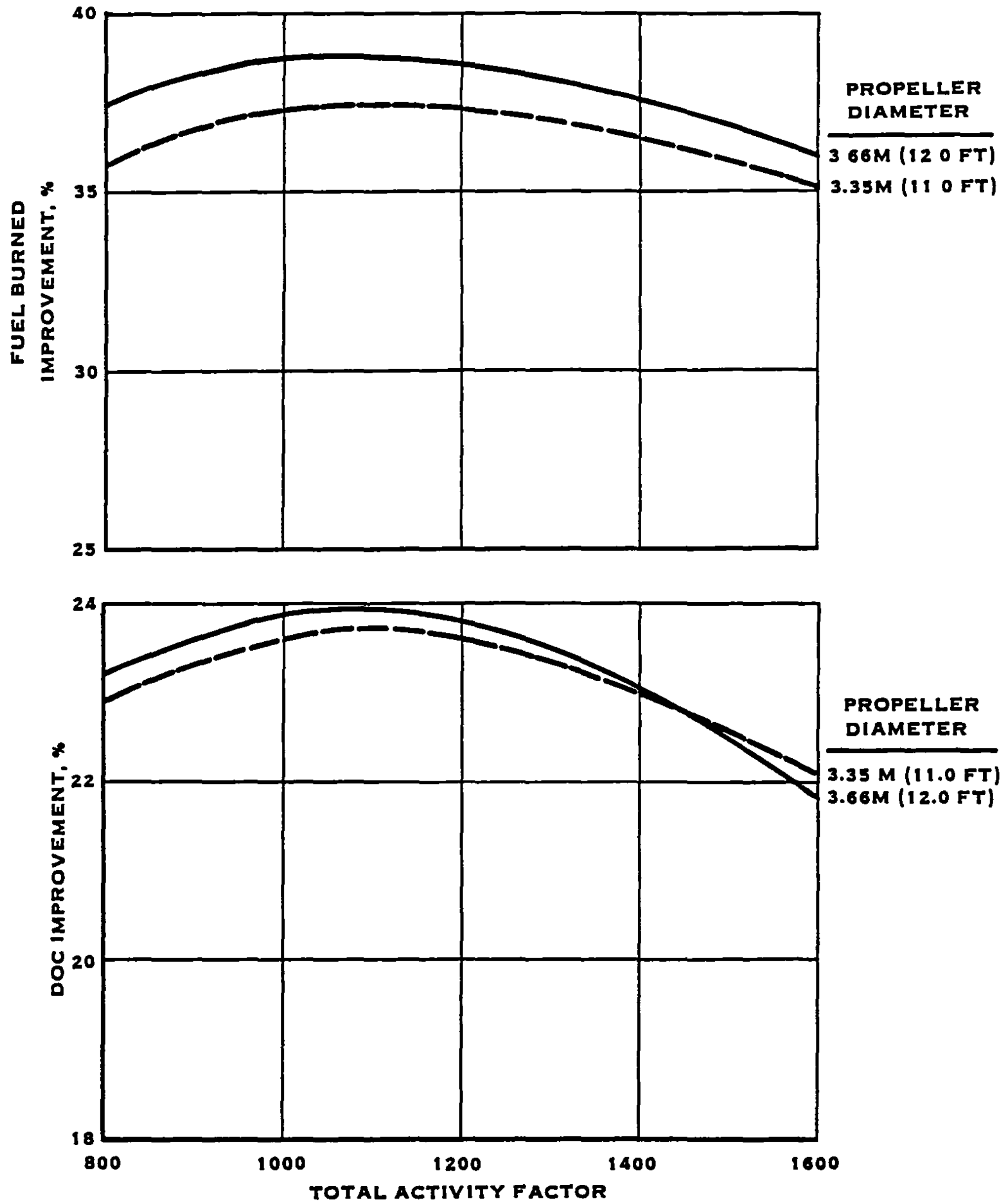


FIGURE 39. EFFECT OF PROPELLER DIAMETER AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION PROPELLER; NO PROPLETS, TIP SWEEP = 45°, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

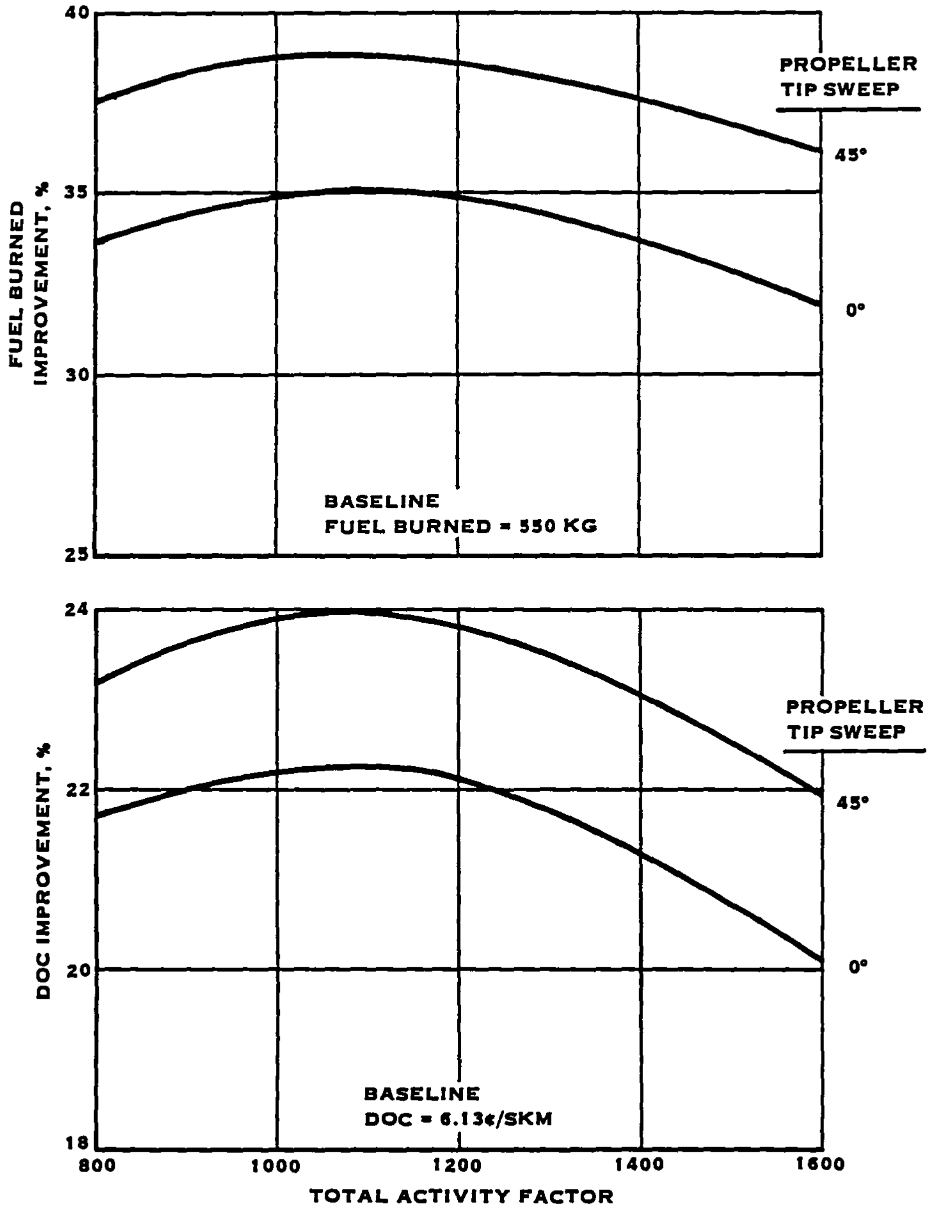


FIGURE 40. EFFECT OF TIP SWEEP AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

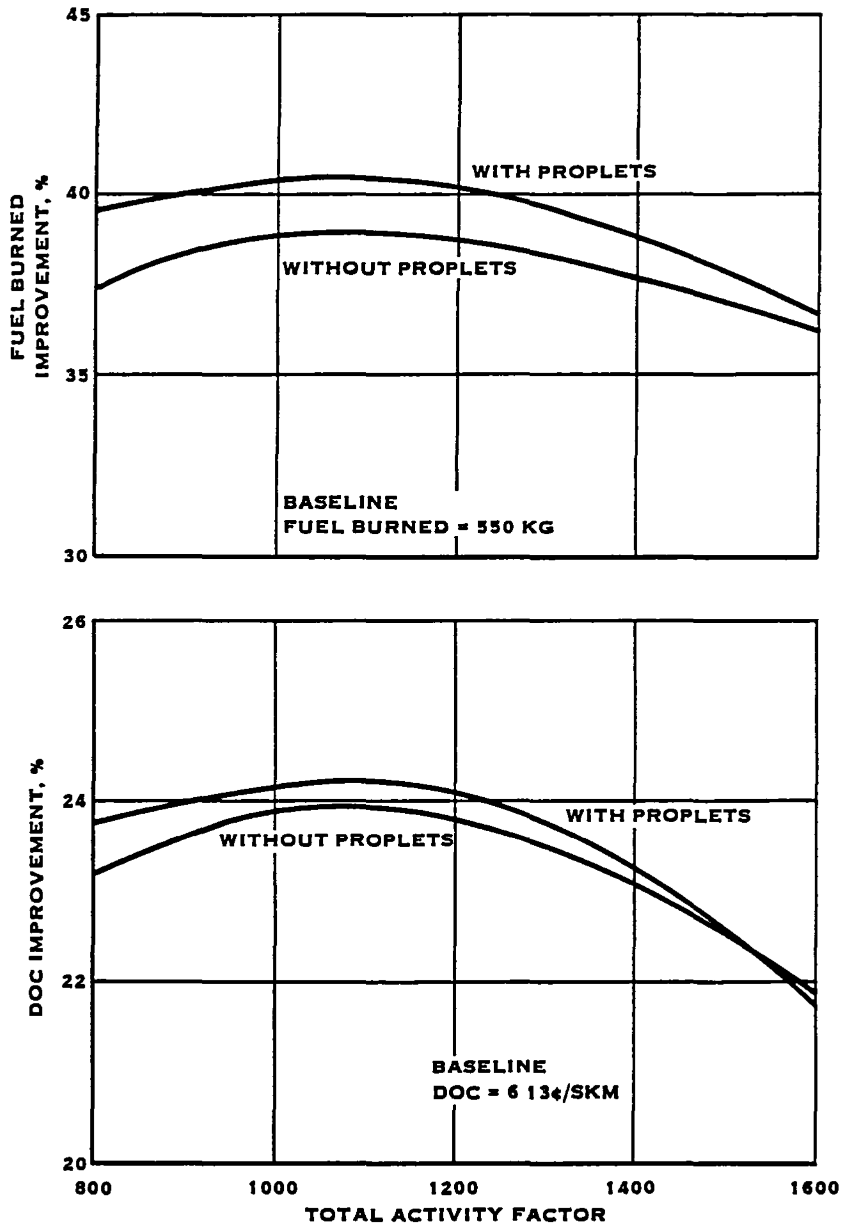


FIGURE 41. EFFECT OF PROPLETS AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; TIP SWEEP = 45°, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

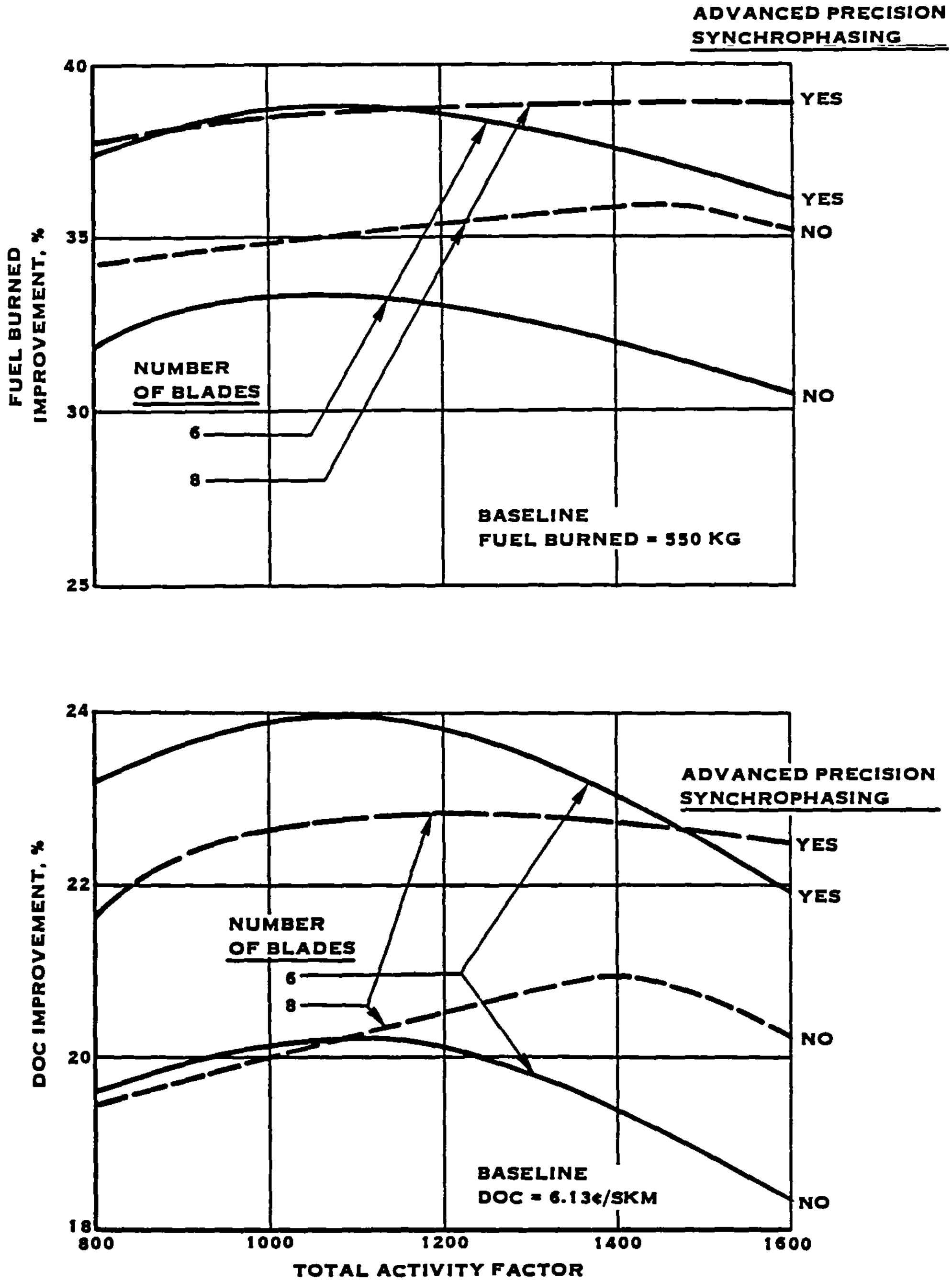


FIGURE 42. EFFECT OF ADVANCED PRECISION SYNCHROPHASING AND TOTAL ACTIVITY FACTOR ON DIRECT OPERATING COST AND FUEL BURNED; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; NO PROPLETS, TIP SWEEP = 45°, ADVANCED COMPOSITE MATERIAL, OPTIMUM CAMBER, NUMBER OF BLADES = 6, ADVANCED AIRFOILS; CRUISE = TAKE-OFF TIP SPEED

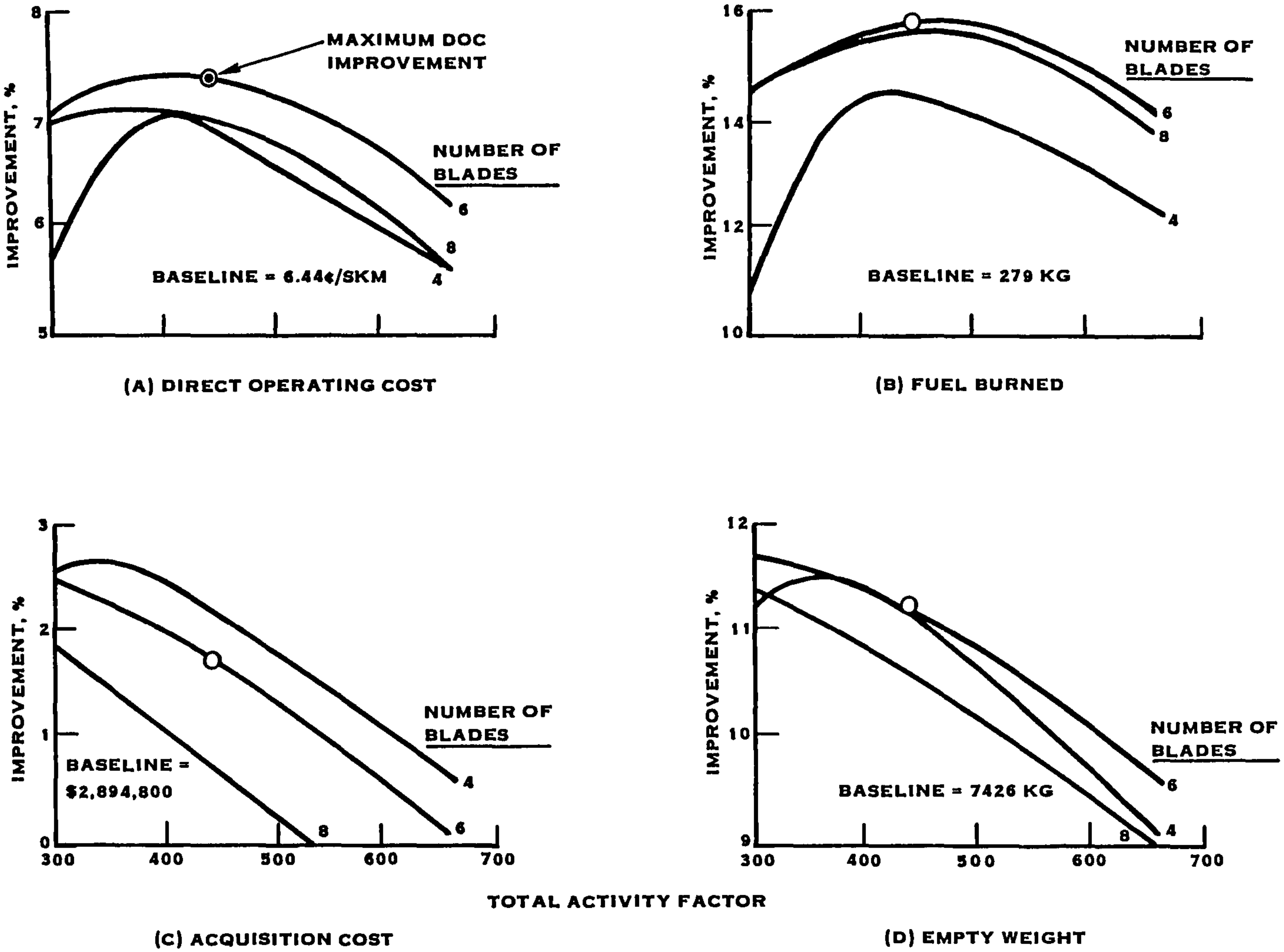


FIGURE 43. PROPELLER OPTIMIZATION TRENDS; CONVAIR 30 PAX, 0.47 MACH AIRPLANE; SINGLE ROTATION, 3.50M (11.5 FT) DIAMETER PROPELLER; NO SWEEP, PROPLETS, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, ADVANCED AIRFOILS, IMPROVED ROOTS

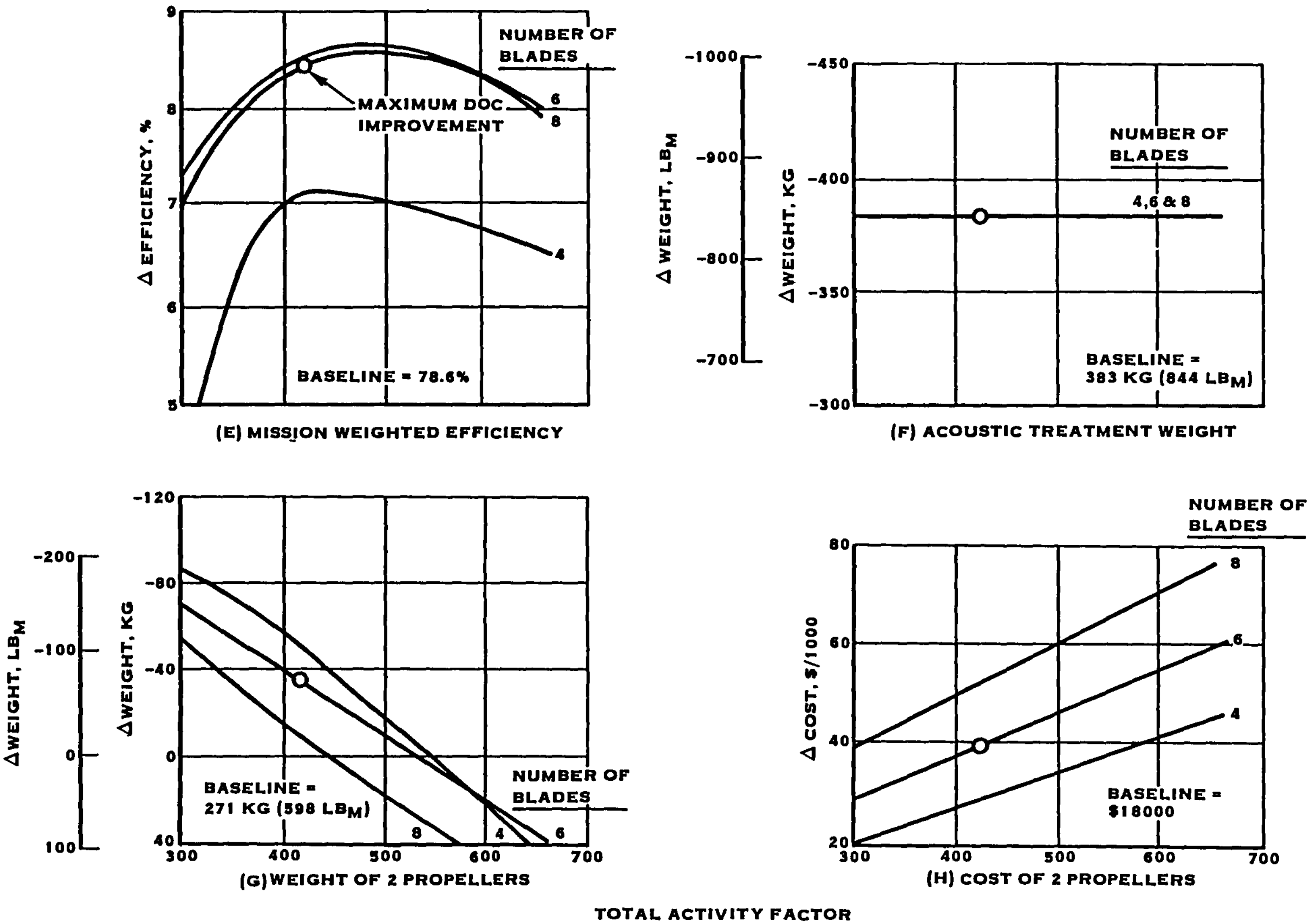


FIGURE 43. (CONTINUED)

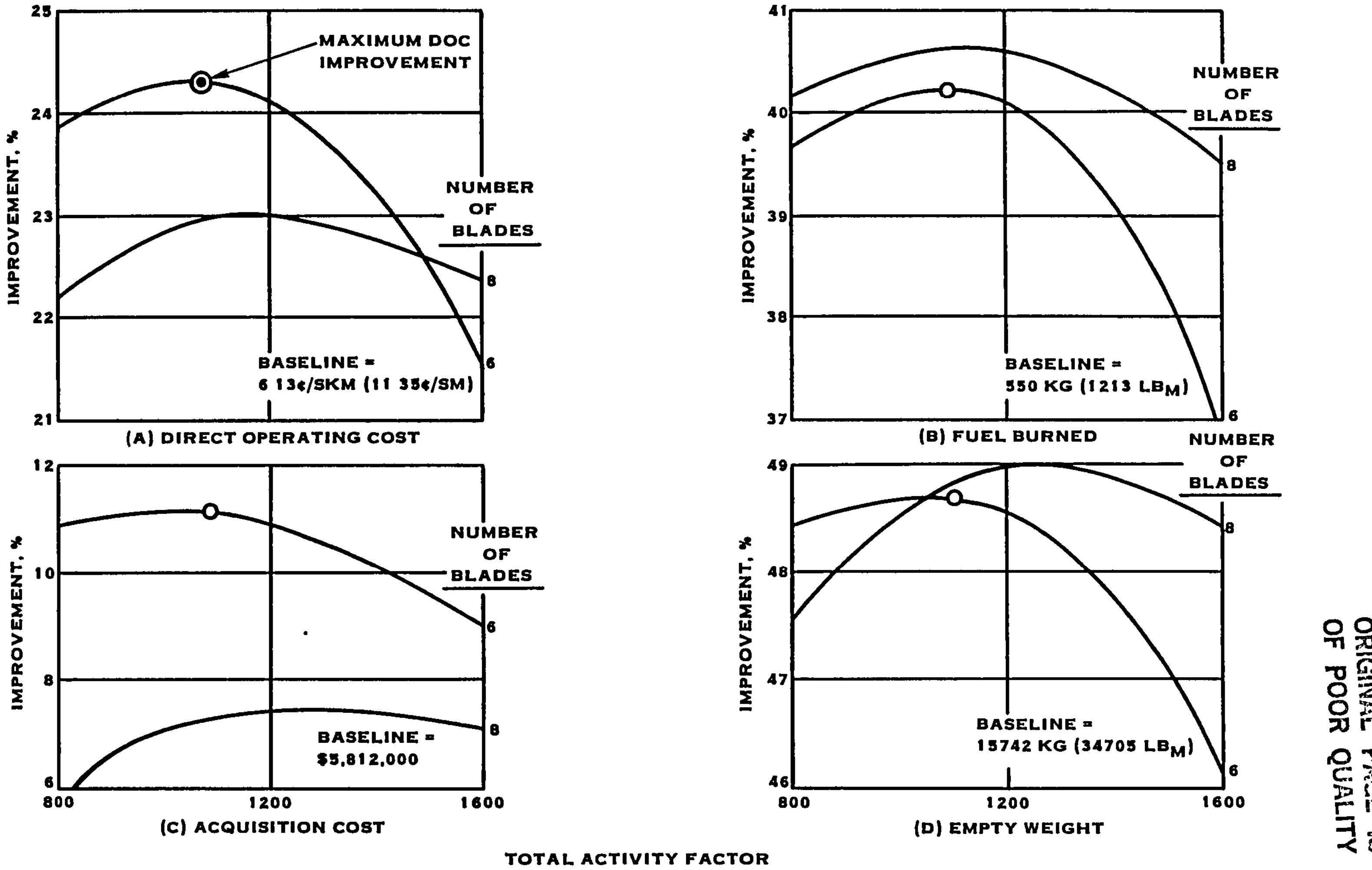


FIGURE 44. PROPELLER OPTIMIZATION TRENDS; LOCKHEED 50 PAX, 0.70 MACH AIRPLANE; SINGLE ROTATION, 3.66M (12.0 FT) DIAMETER PROPELLER; PROPLETS, TIP SWEEP = 45°, ADVANCED COMPOSITE MATERIAL, ADVANCED PRECISION SYNCHROPHASER, OPTIMUM CAMBER, ADVANCED AIRFOILS

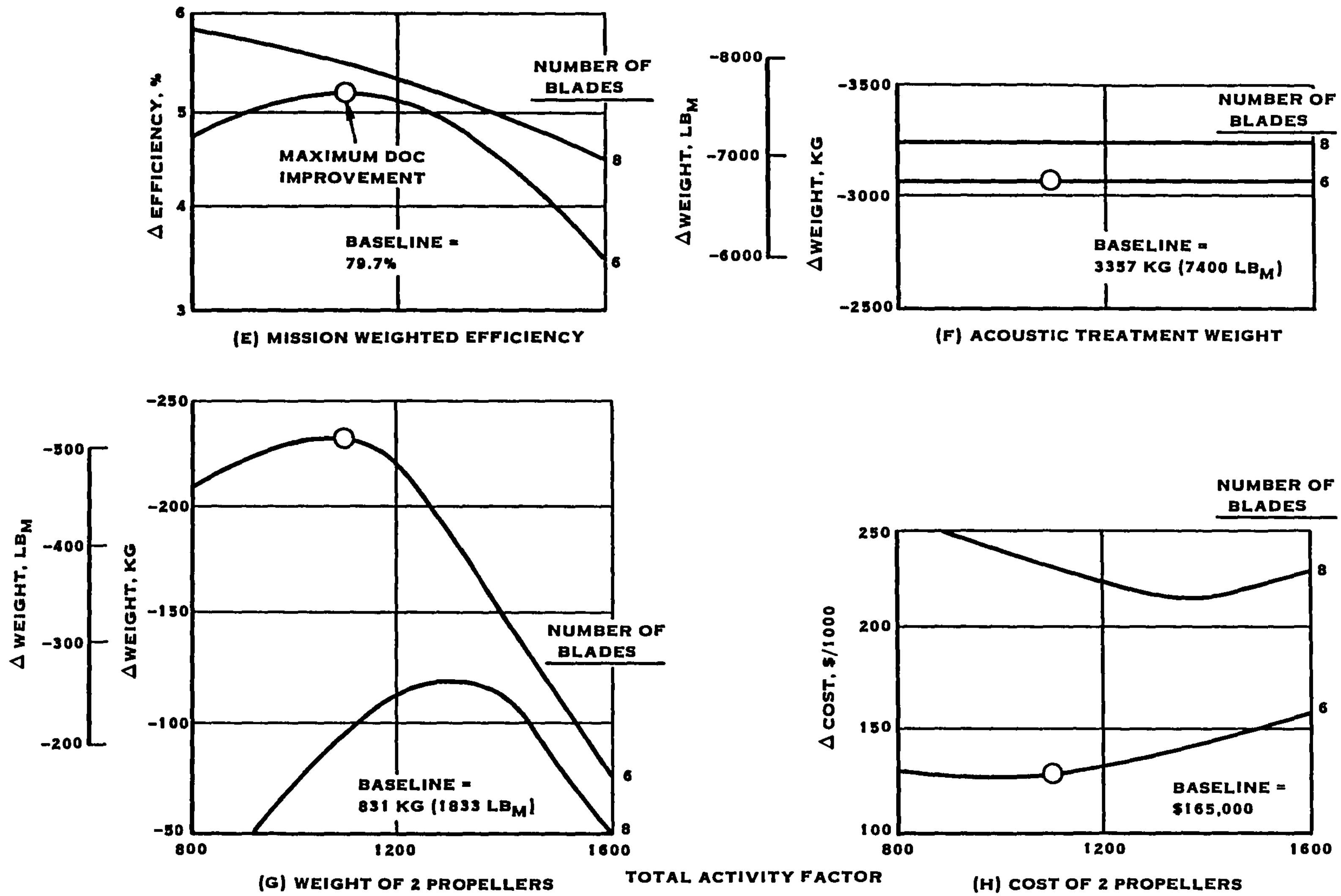
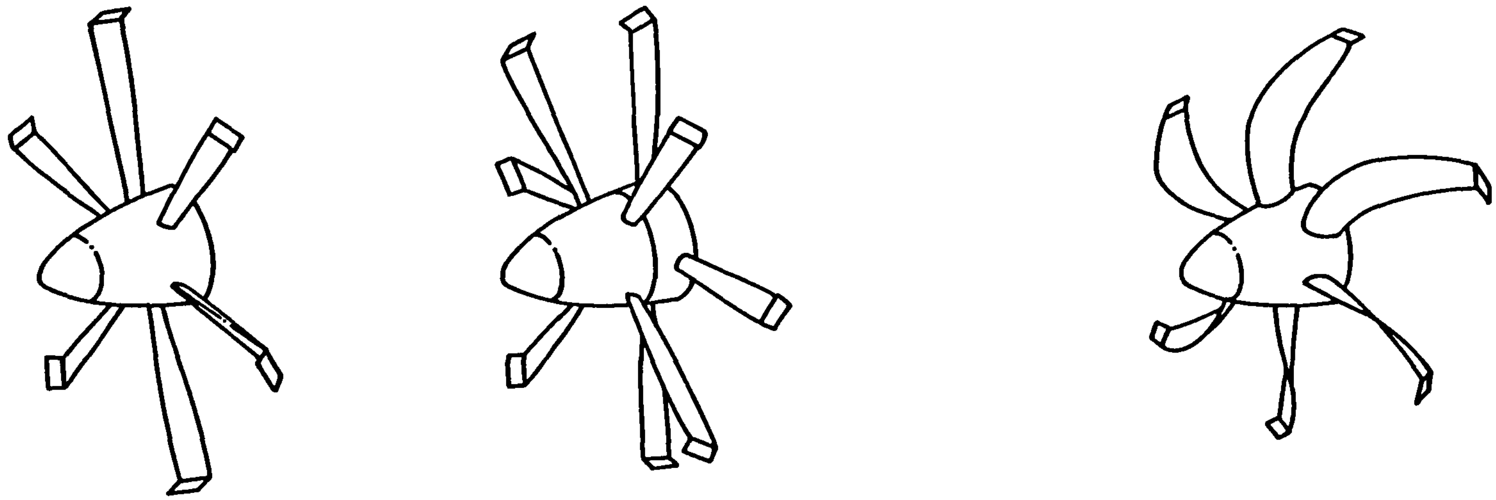


FIGURE 44. (CONTINUED)

CONVAIR 30 PAX
0.47 MACH AIRPLANE

LOCKHEED 50 PAX
0 70 MACH AIRPLANE



SINGLE ROTATION

COUNTER ROTATION
(ALTERNATE CHOICE)

SINGLE ROTATION

ADVANCED PRECISION SYNCHROPHASING →

ADVANCED COMPOSITE MATERIAL →

ADVANCED AIRFOILS →

CRUISE TIP SPEED =	221 M/S (725 FT/SEC)	183 M/S (600 FT/SEC)	190 M/S (623 FT/SEC)
TOTAL ACTIVITY FACTOR =	420	420	1050

FIUGRE 45. ADVANCED TECHNOLOGY PROPELLER SELECTIONS FOR STAT AIRPLANES

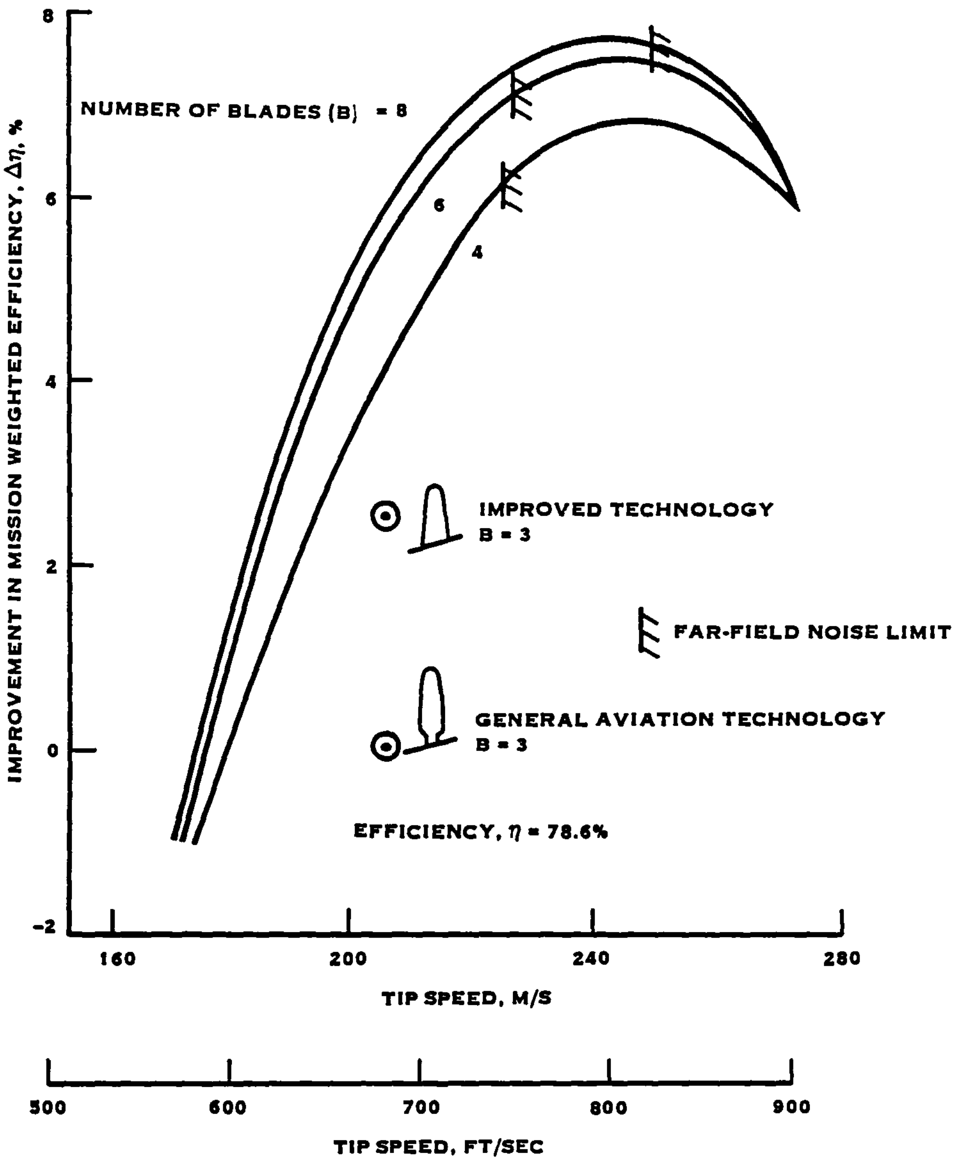


FIGURE 46. EFFECT OF BLADE NUMBER AND SHANK GEOMETRY ON PERFORMANCE; CONVAIR 30 PAX, 0.47 MACH AIRPLANE

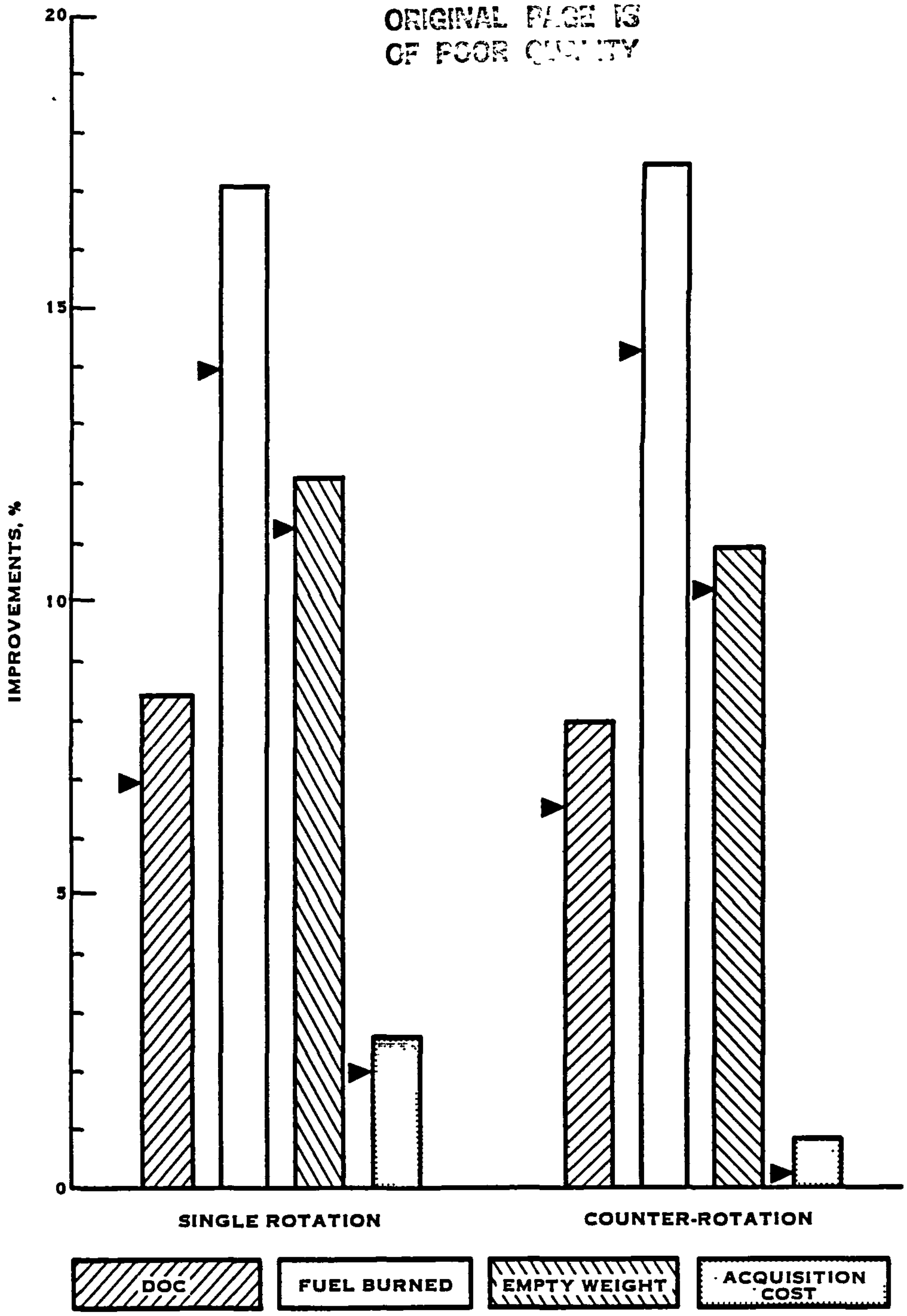


FIGURE 47. AIRPLANE IMPROVEMENTS FOR CONVAIR 30 PAX, 0.47 MACH AIRPLANE RESULTING FROM TWO ADVANCED TECHNOLOGY PROPELLER SELECTIONS; BARS DENOTE TASK I STUDY BASELINE WITH ROUND SHANK PROPELLERS AND MARKS (▶) DENOTE BASELINE WITH AIRFOIL SHANK PROPELLERS

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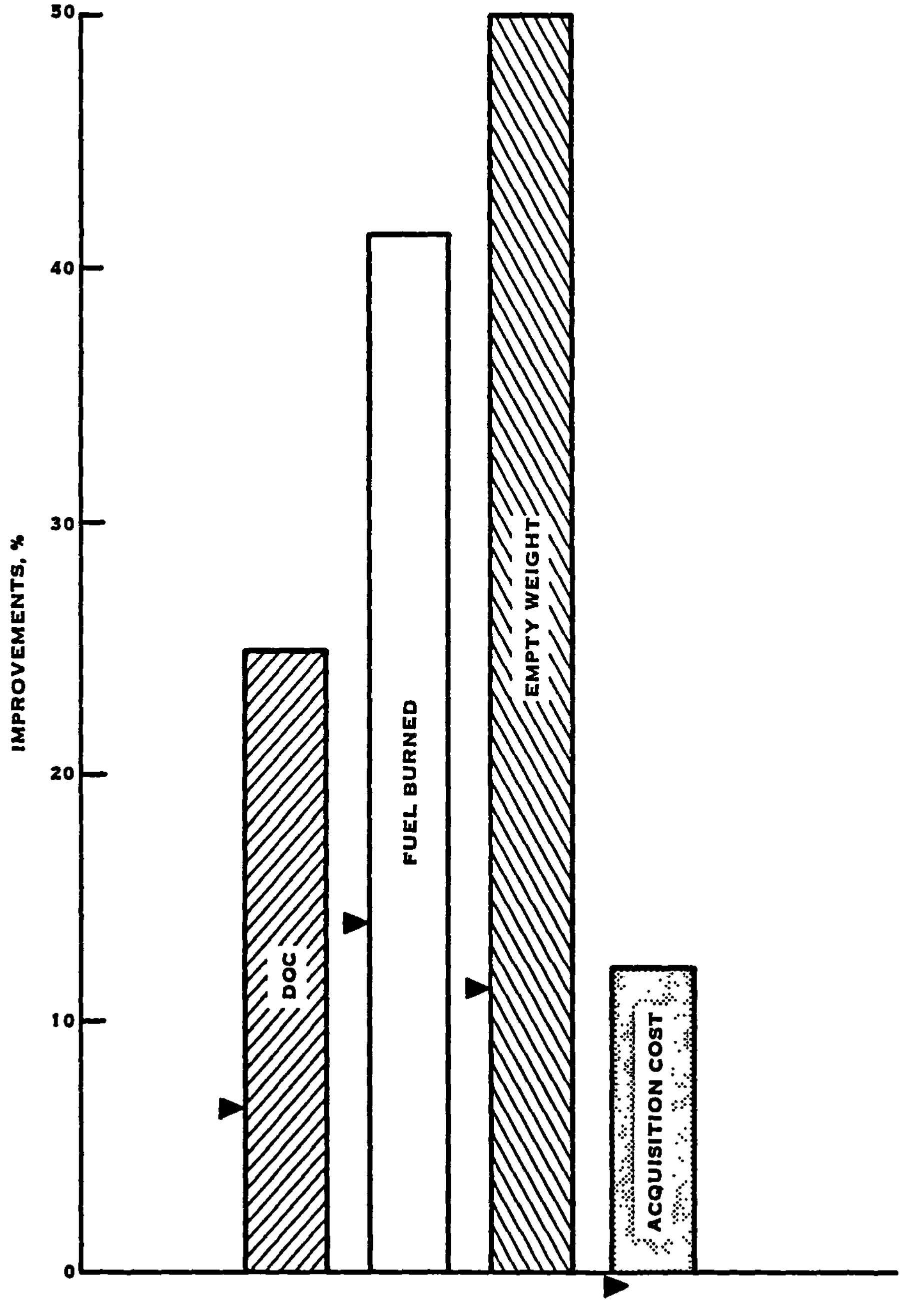
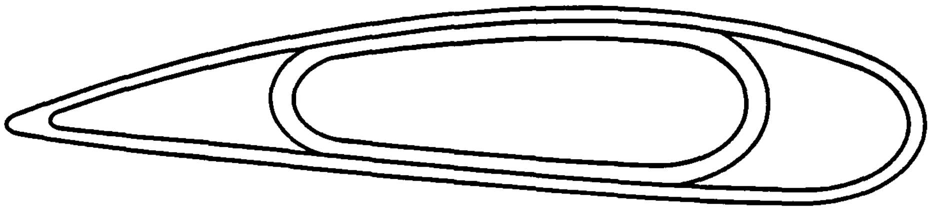
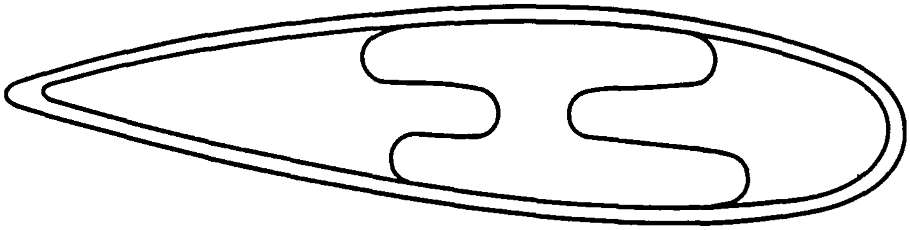


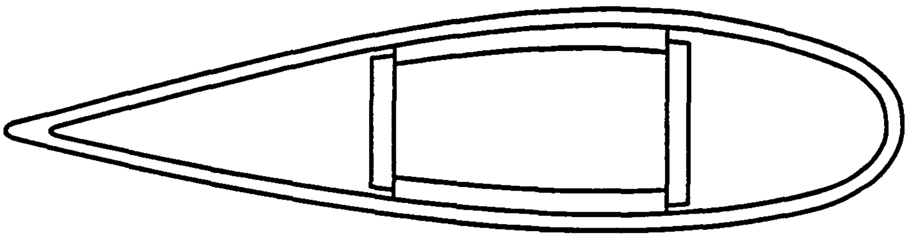
FIGURE 48. AIRPLANE IMPROVEMENTS FOR LOCKHEED 50 PAX, 0.70 MACH AIRPLANE RESULTING FROM ADVANCED TECHNOLOGY PROPELLER SELECTION; BARS DENOTE TASK I STUDY BASELINE HAVING 3357 KG (7400 LBM) ACOUSTIC TREATMENT AND MARKS (▶) DENOTE BASELINE HAVING 680 KG (1500 LBM) ACOUSTIC TREATMENT; LATTER BASELINE EXCEEDS CABIN NOISE OBJECTIVE BY 13dB



(A) HOLLOW SPAR



(B) SCALLOPED SPAR



(C) BUILT-UP BOX SECTION

FIGURE 49. ILLUSTRATION OF SEVERAL LIGHTENED SPAR TECHNIQUES APPLICABLE TO SPAR-SHELL BLADE CONCEPTS

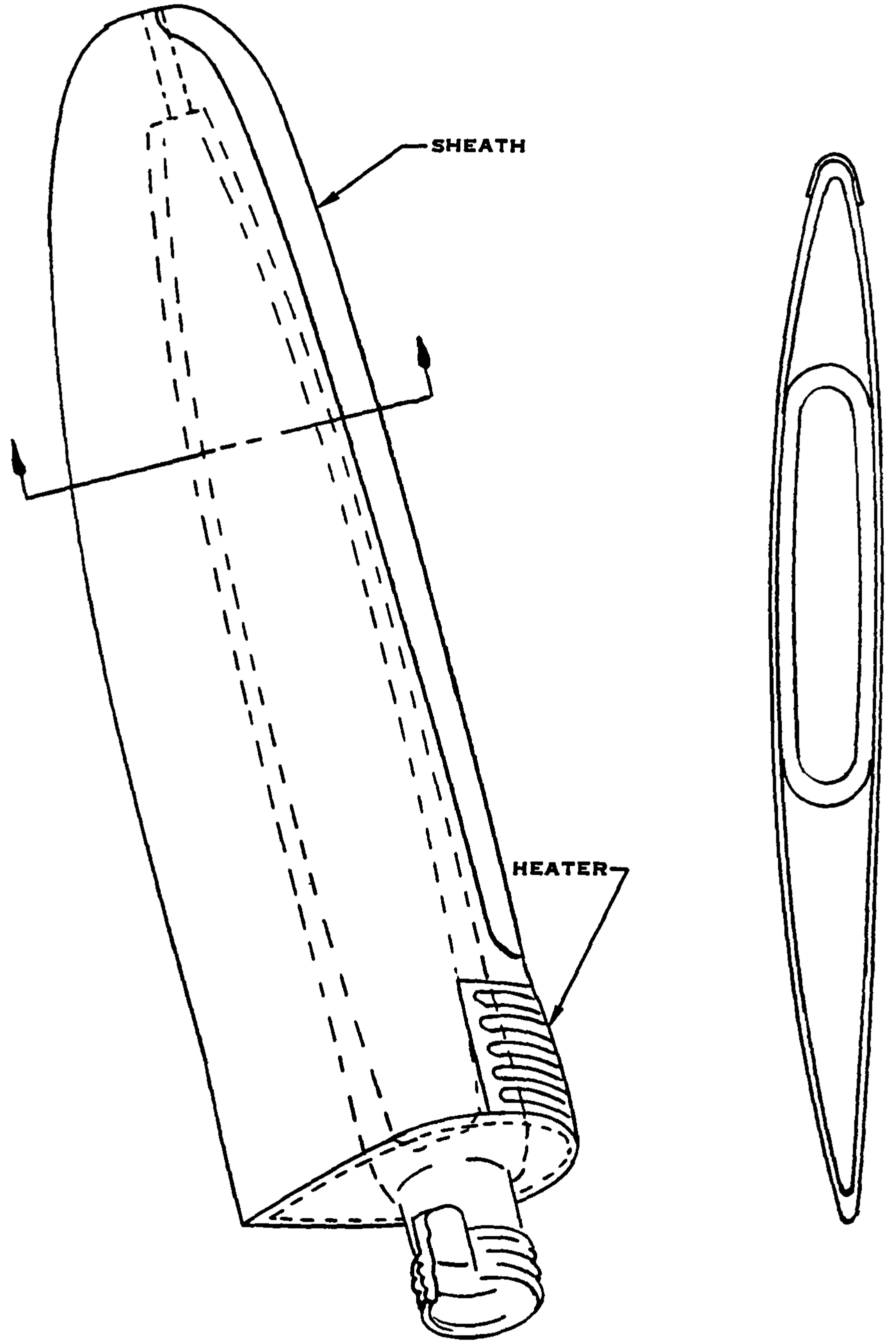


FIGURE 50. ILLUSTRATION OF HOLLOW SPAR-SHELL BLADE DESIGN INCLUDING SHEATH, HEATER AND RETENTION

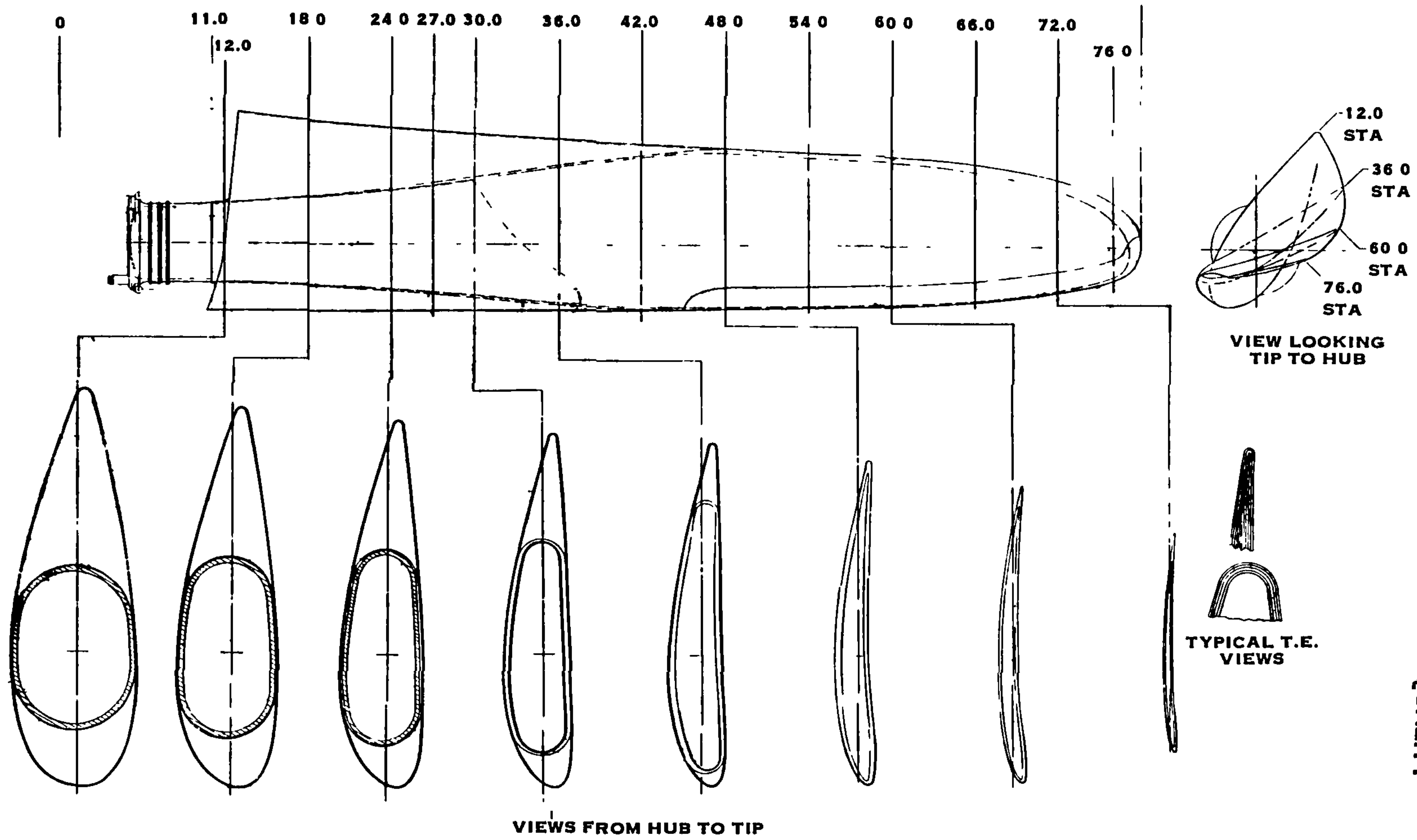


FIGURE 51. AIRFOIL VERSUS RADIUS DEFINITION FOR A HOLLOW STEEL SPAR COMPOSITE SHELL DESIGN

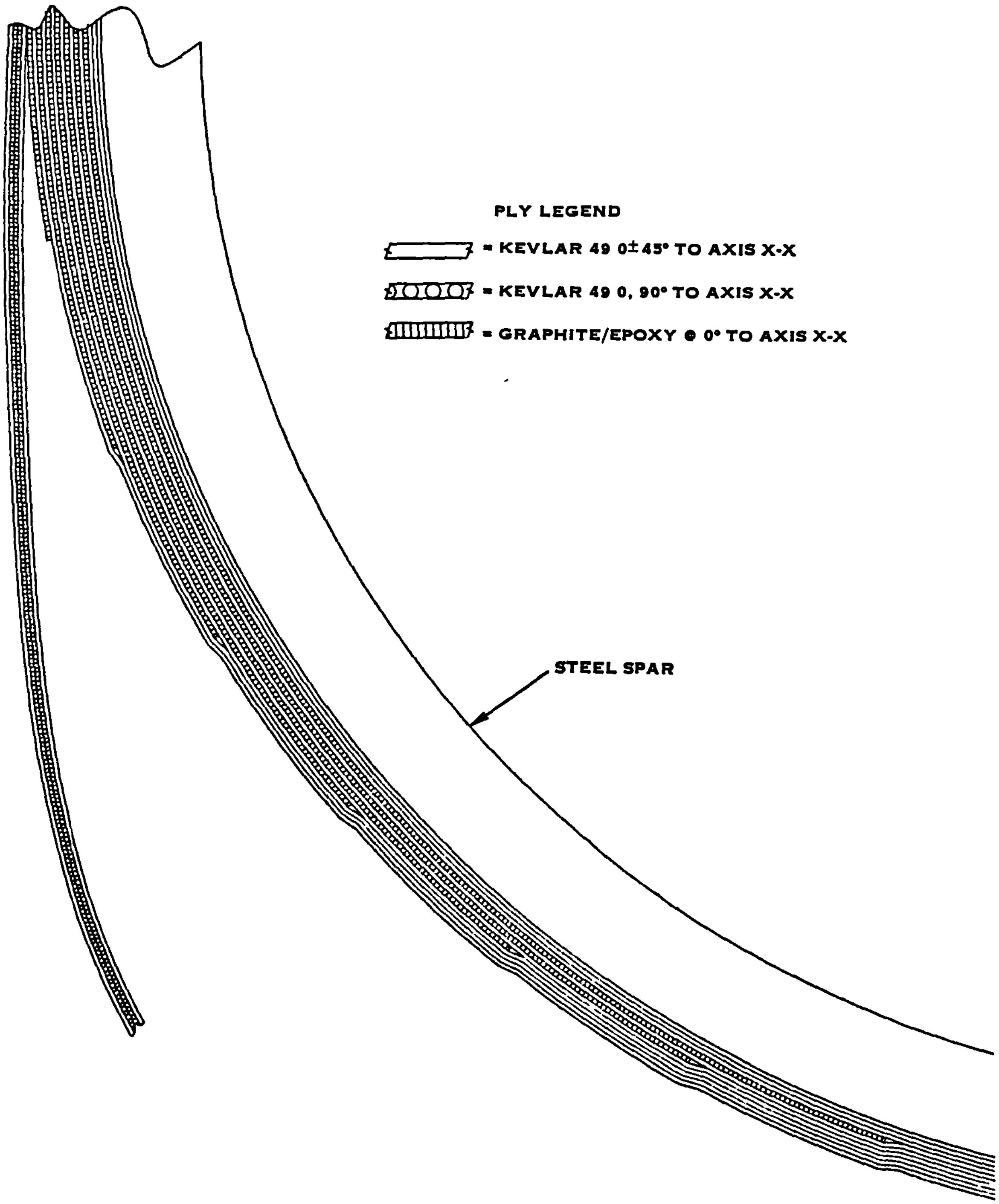
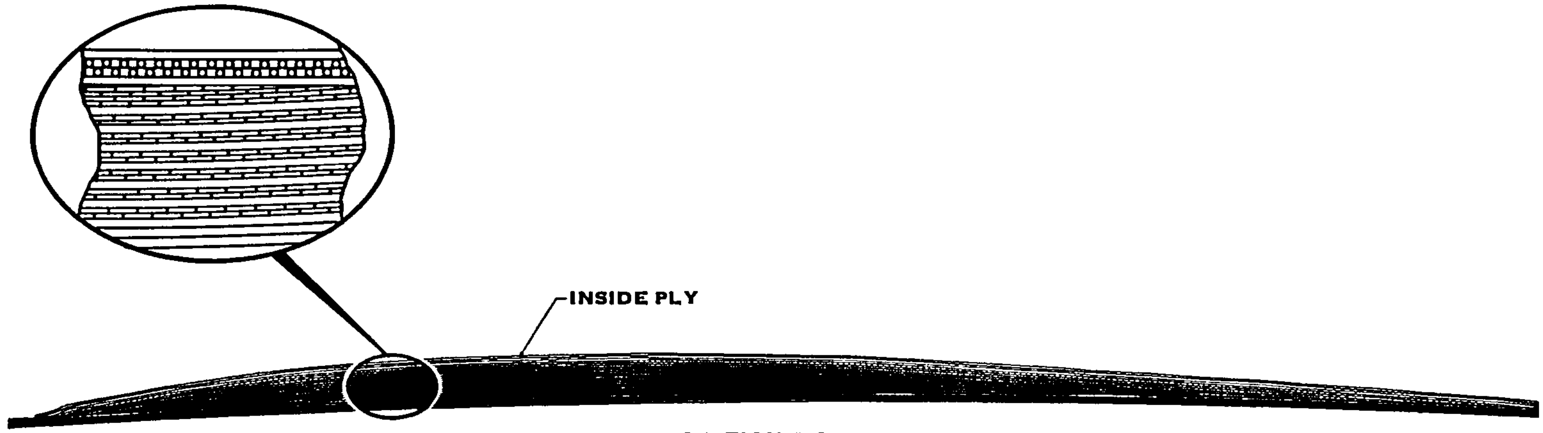


FIGURE 52. SCHEMATIC OF JUNCTURE OF COMPOSITE SHELL AND STEEL SPAR



SECTION A-A

FACE SIDE ONLY (SCHEMATIC) SHOWING LAYER DISTRIBUTION INCLUDING OUTER FOUR PLYS

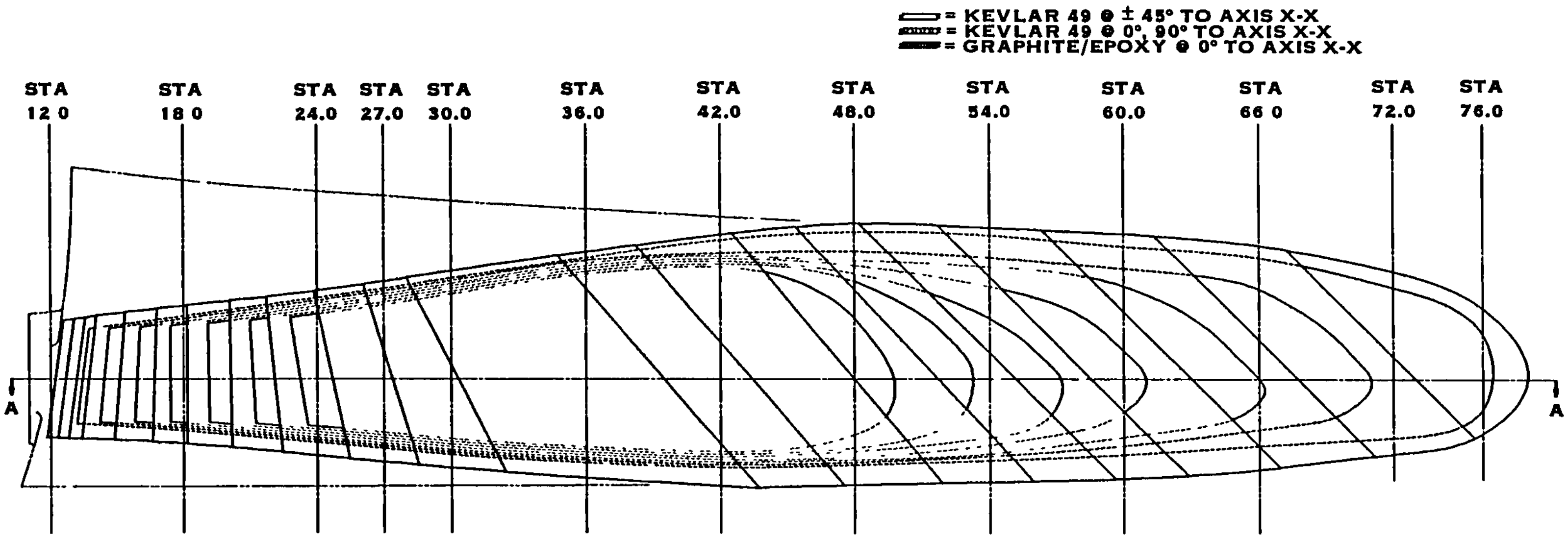


FIGURE 53. DEVELOPED PLAN FORM WITH OUTER FOUR PLYS REMOVED FOR CLARITY

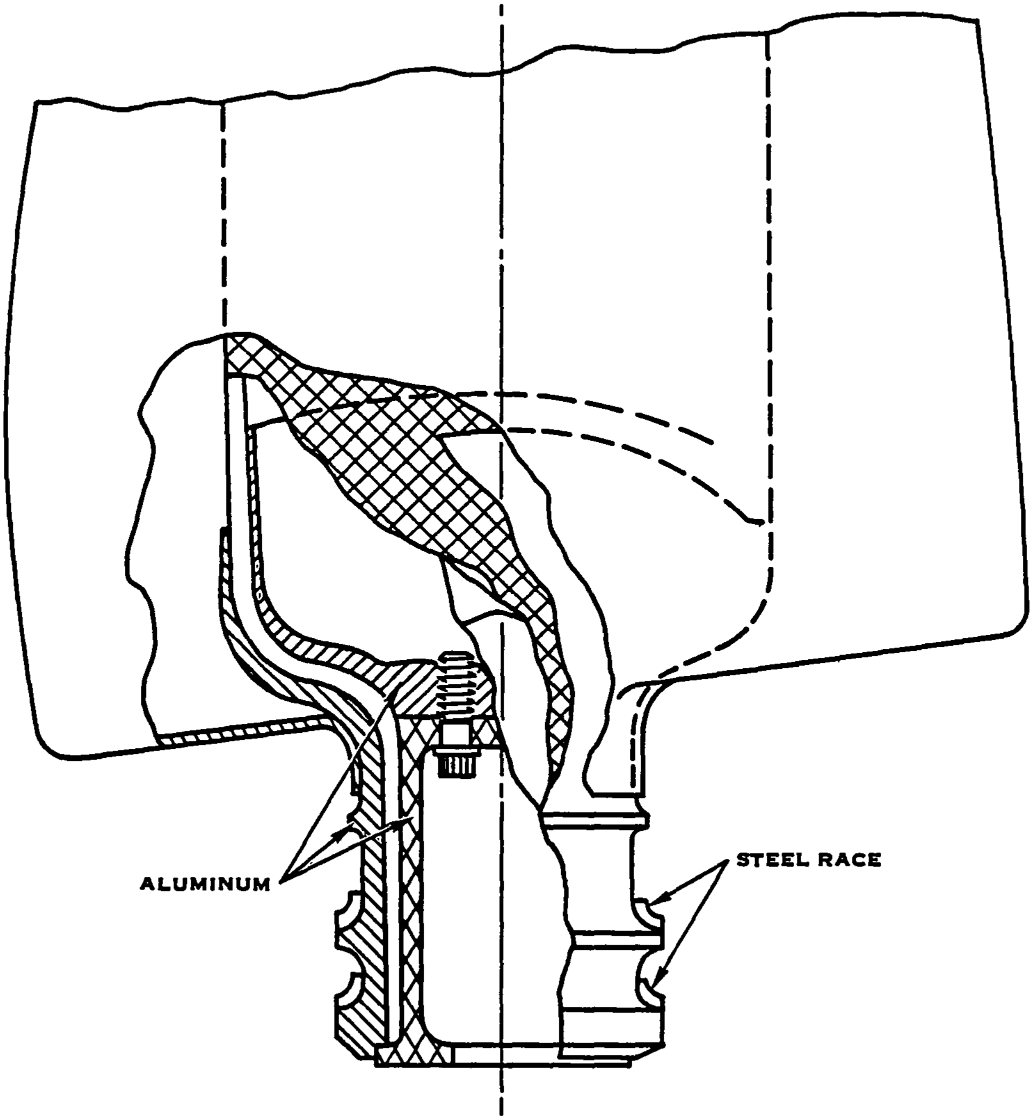


FIGURE 54. ILLUSTRATION OF BLADE RETENTION CONCEPT APPLICABLE TO COMPOSITE SPAR-COMPOSITE SHELL DESIGN

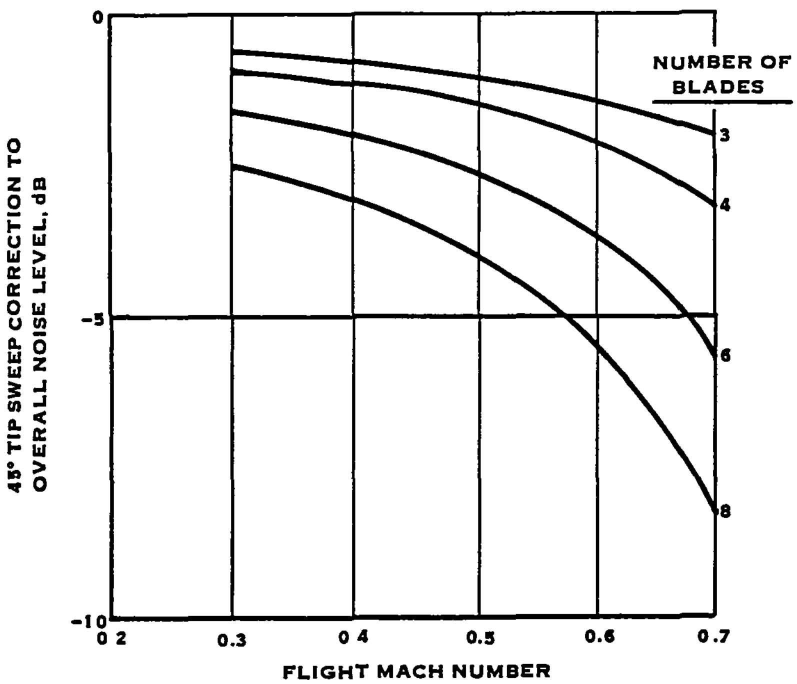


FIGURE 55. TIP SWEEP CORRECTION TO PROPELLER OVERALL NEAR-FIELD NOISE LEVEL

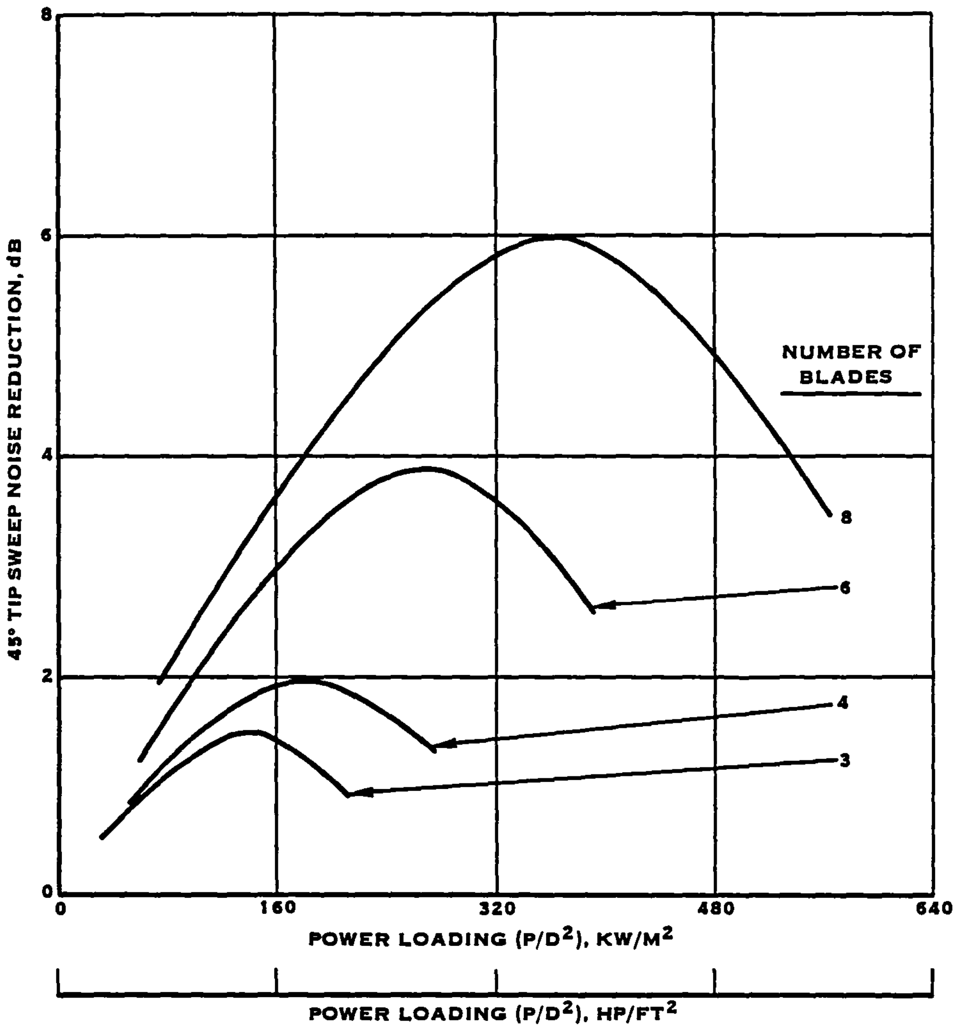


FIGURE 56. TIP SWEEP CORRECTION TO PROPELLER FAR-FIELD NOISE LEVEL

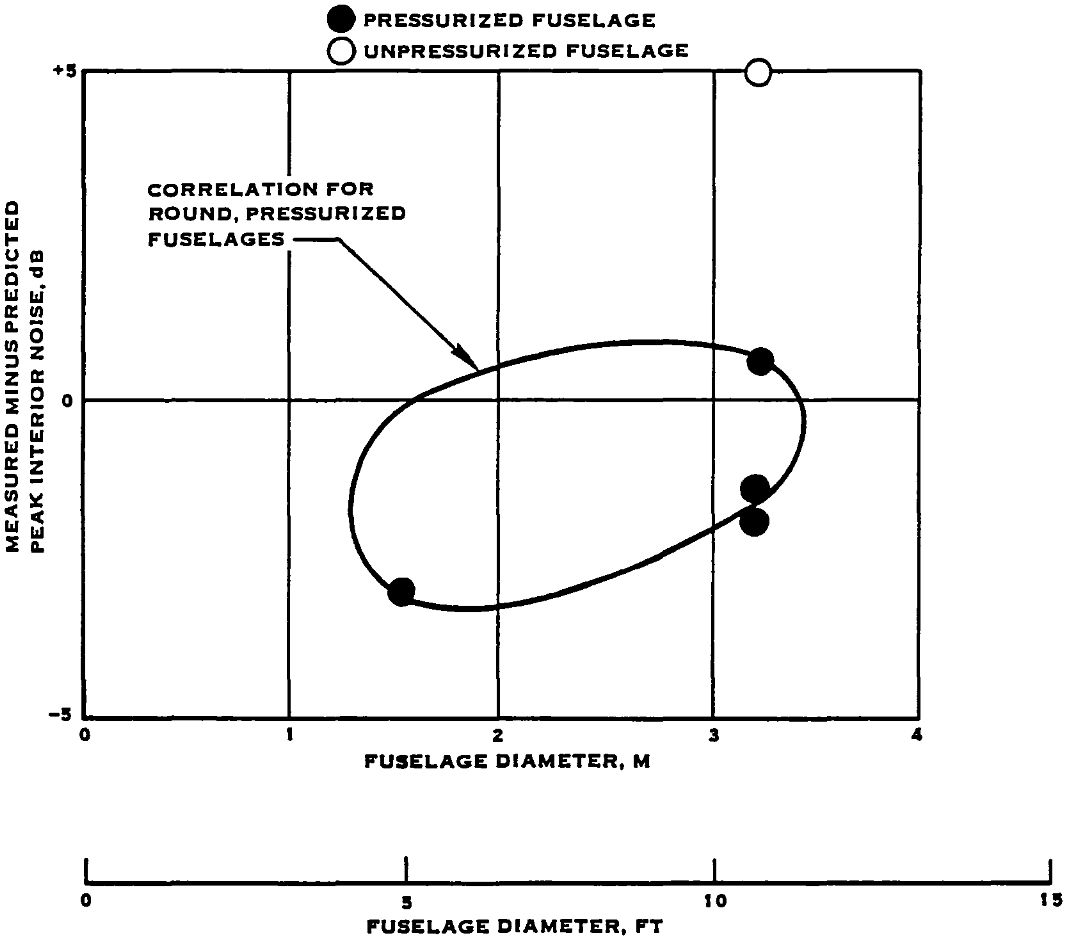


FIGURE 57. CORRELATION OF PREDICTED AND MEASURED INTERIOR NOISE LEVELS FOR PROPELLER DRIVEN AIRPLANES

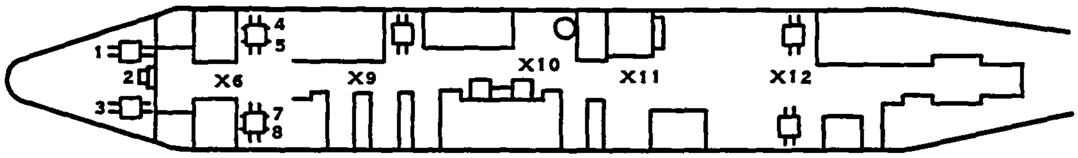


FIGURE 58. MEASUREMENT LOCATIONS FOR THE SYNCHROPHASER EVALUATION

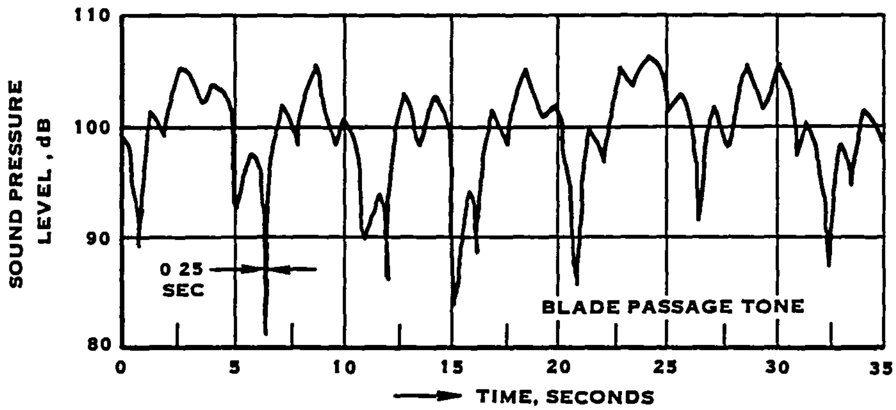


FIGURE 59. NOISE LEVEL VARIATION DUE TO PROPELLER PHASE ANGLE CHANGES

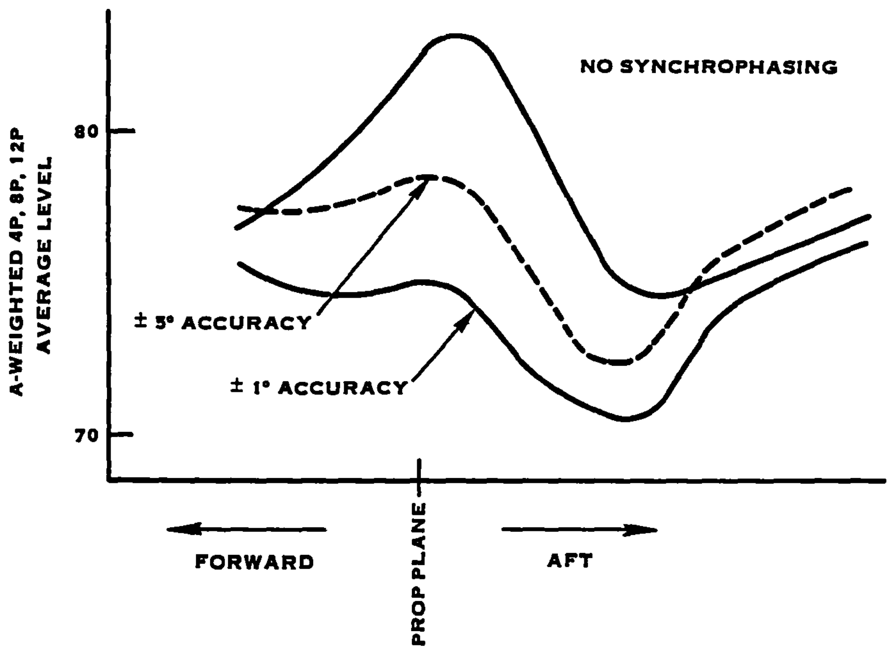


FIGURE 60. EFFECT OF SYNCHROPHASER ACCURACY ON CABIN NOISE REDUCTION

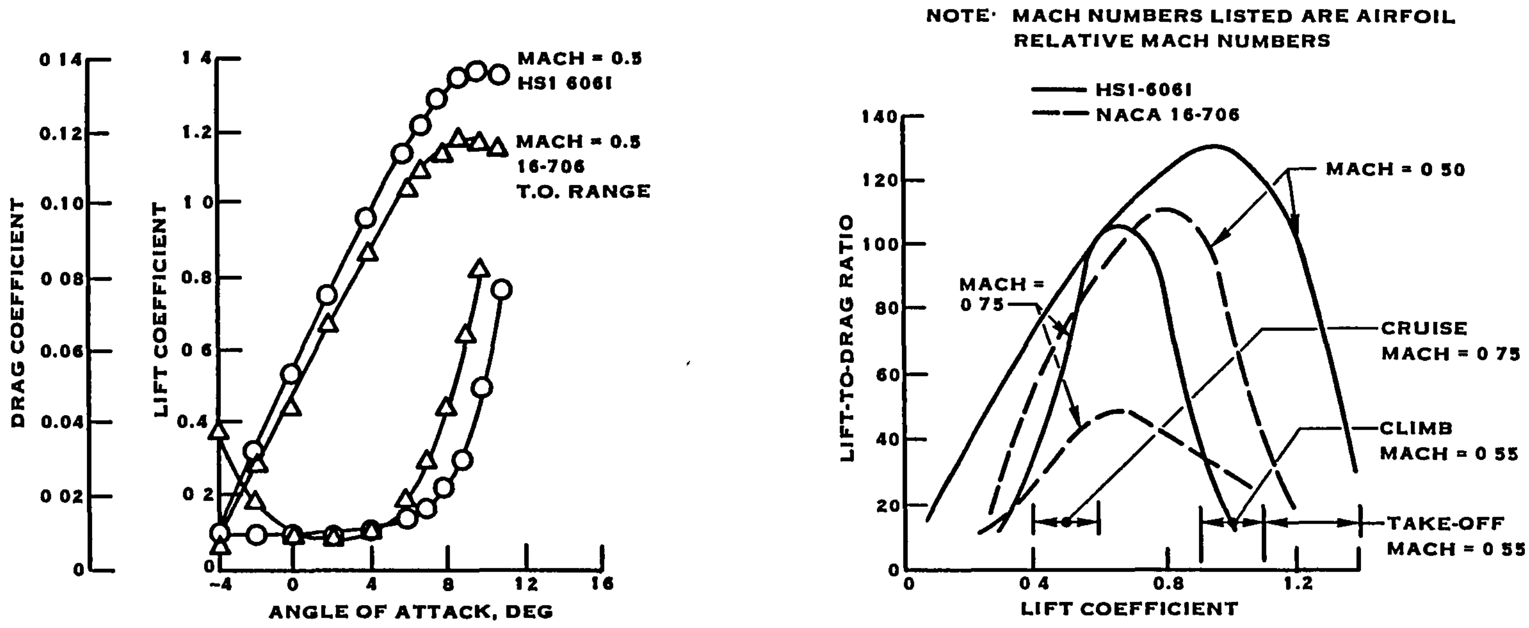


FIGURE 61. AIRFOIL PERFORMANCE COMPARISONS FROM TEST DATA FOR ADVANCED AND CURRENT AIRFOIL SHAPES

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