Swept Tip Design Trade Study -
New Affordable Main Rotor Blade for the AH-64D Apache Attack Helicopter

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ABSTRACT

An in depth trade study was conducted to determine the best design and construction methodology for the swept tip structure of a new composite main rotor blade for the AH-64D Apache Longbow Attack Helicopter. The selection was influenced by the cost reduction and improved performance goals of the Affordable Apache Rotor Program (AARP). The results of this study established the design configuration that was carried forward into the detail design and fabrication of the AARP main rotor blades. The bonded swept tip leading edge design option was selected over the mechanically fastened options because it provides the best opportunity for meeting the acquisition cost, operation and support (O&S) cost and system performance goals of the AARP program while fulfilling the operational requirements of the AH-64D Apache Longbow helicopter. None of the design options that were investigated provided the best solution in all categories examined in the study. The chosen design solution was determined to offer the best combination of design characteristic while offering the lowest projected total life cycle cost to the U.S. Army.

INTRODUCTION

The goal of the Affordable Apache Rotor Program (AARP) is to design and test a replacement rotor blade for the AH-64D Apache Longbow Attack Helicopter. The design requirements for the new blade are to achieve lower system acquisition cost and operations and support (O&S) cost as compared to the current Apache Longbow main rotor blade. The new blade is also designed to provide increased performance to regain operational capability and to accommodate future heavier versions of the aircraft.

In an attempt to meet the affordability goals, as well as fulfill the requirements of the Apache Longbow system specification, many trade studies were conducted during the preliminary design process. One area of the blade that presented an opportunity for a number of design solutions was the construction of the aerodynamically swept structure of the main rotor blade tip. Selection of the final design solution required a careful examination of the system requirements, impact on the cost and weight goals of the AARP contract, input from the customer and user community, usage history and lessons learned from the current Apache blade design and other military helicopter blades.

A detailed analysis was conducted for three separate design concepts. Each concept maintained the same aerodynamic configuration but varied the method of construction and installation. The three options were selected in order to examine the extremes of the design options. Virtual geometric models were constructed with computer aided design and assembly tools. These models became the basis for the analytical comparisons. The most significant variable between the concepts was the method of mechanical attachment of the swept tip to the main inboard section of the blade. This single design variable has significant impact on the weight, structural design, dynamic tuning, manufacturing methods, manufacturing cost and predicted O&S cost including reliability, maintainability and repair ability.

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BACKGROUND

The aerodynamic configuration of the AARP main rotor blade design utilizes swept and tapered plan form geometry at the tip of the blade (see Figure 1). The sweep and taper both initiate at 92% rotor radius and terminate at the tip (100% radius = 288.00 inches). Inboard of 92% radius, the blade has a constant aerodynamic shape. This constant portion of the blade consists of a 10% thick VR-22E airfoil with a 21.00-inch chord length and a twist rate of .04167 degrees per inch (see Figure 2a). The swept portion is a linear transition from the VR-22E airfoil at 92% radius to a 7.5% thick HH-13 airfoil at the tip of the blade. The tip chord length of the HH-13 airfoil is 13.00 inches. The blade sweeps aft from the leading edge at a 20-degree angle (at the ¼ chord) and does not twist outboard of 92% rotor radius.

The blade design incorporates abrasion resistant metallic material along the leading edge. This feature is required to meet the sand and water erosion requirements that are defined by the Apache Longbow System Specification. The thin metal material of this abrasion strip extends aft of the leading edge of the blade in a chordwise direction on the upper and lower surfaces. It provides erosion protection for the structural composite material behind the abrasion strip. The spanwise duration of the abrasion strip starts at the inboard end of the blade and extends to the tip.

It was determined early in the design process that the leading edge abrasion strip would be easier and less expensive to fabricate in two separate pieces. One long straight section is formed for the constant spanwise section of the blade. The outboard portion of the blade span is protected with a second piece that is formed to the transition contour of the swept tip. The location of the joint between the inboard and outboard segments of the abrasion strip is located slightly inboard of the contour transition at 92% rotor radius.

The inboard segment of the leading edge abrasion strip is an integral part of the blade structure and is permanently bonded to the underlying composite structure. The outboard swept tip leading edge abrasion strip had the option of being attached to the blade structure in a number of different ways. Three design options were developed to investigate the attachment of the swept tip leading edge (see Figure 3). All three options utilize an electro-formed nickel shell detail for the swept tip leading edge. The current AH-64D Apache blade design utilizes nickel-plated Inconel for the swept tip leading edge. The thickness of the swept tip leading edge material for the AARP blade design is approximately 50% thicker than the current Apache blade. The additional thickness was incorporated in the design of the AARP main rotor blade is to improve the erosion life at the blade tip.

All of the design options for the tip construction require a leading edge counter balance weight to compensate for the aft center of gravity (C.G.) of the swept tip plan form. This counter balance weight is not adjustable and is located at the extreme leading edge of the blade just inboard of 92% rotor radius. The three proposed swept tip design options also include an adjustable tip weight feature. An adjustable tip weight fitting (or fittings) is also located within the composite spar structure just inboard of 92% rotor radius for each option. This fitting features accessible pockets that will locate and secure variable amounts of adjustable weights forward and aft of the chordwise balance location at the constant section quarter chord. Weight adjustment is required at the tip end of each rotor blade to provide proper spanwise and chordwise mass balance. The configuration of the adjustable tip weight fitting differs for each of the three proposed design options.

The leading edge counter balance weight and the adjustable tip weights and fittings are all located inboard of the tip sweep for two primary reasons. Locating this mass inboard of the sweep allows the weights to be located in the proper chordwise position without compromising the dynamic mass balance about the quarter cord of the constant section. Positioning the tip weights inboard of the sweep also makes them less vulnerable to damage or loss due to blade tip strikes. This feature is a carried over from the current AH-64D blade design. The design option that utilizes the least amount of weight in the swept tip structure requires the least amount of leading edge counter balance weight and ultimately produce the lightest blade design.

TIP DESIGN OPTIONS

The tip design configurations defined for this examination were based on the options that were identified at the time that this trade study was conducted. Each of the three options was selected to provide the extreme differences in the construction methodology. Other features in the design were held constant for all three options. The purpose for maintaining these constraints was to determine the best construction method without being influenced by characteristic that did not have true impact on the primary factors for this evaluation. This point is significant for the economic analysis that compares the three options in this study.

Although the final configuration of the prototype AARP main rotor blades is based on the configuration that was identified in this examination, the as-built configuration differs slightly because it was no longer bound by the constraints of similarity maintain for the three options in this study. Additional features and improvements were incorporated into the final design that had not yet been identified at the time of this study. Although the final flight version of the AARP swept tip differ slightly, the conclusion of this paper and supporting analysis are still valid since any of the three options would have incorporated the additional features that were subsequently added.

Option A: Bonded Swept Tip Leading Edge

The first option evaluated for the construction of the blade swept tip utilizes adhesive bonding to attach the swept tip leading edge (see Figures 4 & 5). In this option the composite spar structure and inboard abrasion strip end at approximately 92% radius. The metallic shell of the swept tip leading edge abrasion strip provides all of the outboard structure in the leading edge. The aft fairing assembly is continuous from the constant section of the blade through the swept transition to the tip. The aft fairing is composed of the upper and lower aft skins, Nomex core and composite heel channel that forms the aft vertical wall of the spar (see Figure 2b for an exploded view of the components that comprise the structure of the constant blade cross section).

Access to the forward and aft adjustable tip weight pockets with the bonded swept tip leading edge is gained by removal of screw fasteners and cover plate on the lower blade surface just inboard of 92% radius. Lower surface access to the adjustable tip weights is required due to the bonded attachment of the swept tip components (see Figure 6 for details of the tip weight configuration with lower blade surface access). The swept tip leading edge is bonded to the interfacing composite structure of the spar and aft fairing along its perimeter (see Figure 4). This bond operation requires the use of a tooling fixture for correct location and the control of bonding pressure during the cure at elevated temperature. The adhesive used for this connection must have acceptable hot/wet properties to provide a permanent connection for the full operation environment. The bonded swept tip leading edge can be removed and replaced if required due to strike damage or excessive erosion. This bonding operation may not be practical for a field environment and may require Army depot level attention for repair and replacement.

Option B: Removable Swept Tip Leading Edge

The second option for the construction of the blade swept tip utilizes screw fasteners and nut plates to attach the swept tip leading edge (see Figures 7 & 8). Countersunk screws are located around the upper and lower surface perimeter of the removable swept tip leading edge at 54 locations. These fasteners screw into nut-plates that are mounted inside of the interfacing structure at the tip end of the blade. As with the previous tip design option, the composite spar structure and inboard abrasion strip end at approximately 92% rotor radius. The metallic shell of the swept tip leading edge abrasion strip provides all of the outboard structure in the leading edge. Glass/composite doublers are bonded to the inner surface of the swept tip leading edge to increase the thickness and provide sufficient bearing strength at the screw hole locations. The heel component of the aft fairing assembly is segmented into two pieces with a connection just inboard of 92% radius. This is needed to transition the heel material from composite in the constant section of the blade to metal in the swept tip. Metal is required to provide adequate structure for the installation of the nut-plates at this location. The aft skins and core are continuous from the constant section of the blade through the swept transition to the tip.

The configuration of the adjustable tip weight fitting is tailored to facilitate the attachment of the swept tip leading edge with screw fasteners for this design option. This fitting is a single metal component that is installed into the outboard open end of the blade spar. It is retained with adhesive bonding to the inner surfaces of the upper and lower spar laminates. A fail-safe load path is provided by 10 mechanical fasteners that penetrate the spar laminates and capture the fitting. Flanges extend from the upper and lower sides of the outboard end of the fitting and extend beyond the outboard end of the spar. Additional nut plates are mounted on the inner surfaces of these flanges to retain the swept tip leading edge. Access to the adjustable tip weight pockets in the weight fitting is gained by removal of the 54 screws that retain the swept tip leading edge. Removal of the swept tip leading edge is the simplest method for access to the adjustable tip weights with this design option. This tip weight and swept tip leading edge design configurations are similar to the current Apache blade. The swept tip leading edge can be removed and replaced at the unit level – aviation unit maintenance (AVUM). This design option has a part count increase of 147 details and weight increase of 8.7 lbs. per blade over and above **Option A**, the bonded swept tip design.

Option C: Removable Swept Tip Assembly

The third option for the construction of the blade swept tip utilizes screw fasteners and nut plates to attach the entire swept tip of the blade outboard of 92% radius (see Figures 9 & 10). Countersunk screws are located around the upper and lower surface perimeter of the removable swept tip assembly at 36 locations. These fasteners screw into nut-plates that are mounted inside of the interfacing structure at the tip end of the constant blade section. As with the previous two tip design options, the composite spar structure and inboard abrasion strip end at approximately 92% radius. The metallic shell of the swept tip assembly provides all of the outboard structure in the leading edge. Glass/composite doublers are bonded to the inner surface of the swept tip leading edge to increase the thickness and provide sufficient bearing strength at the screw hole locations. The aft fairing assembly also terminates at 92% radius. A flanged metallic rib provides closure to the aft core and structure for the nut-plate installation in the aft fairing. This closure rib is bonded behind the composite heel and to the inner surfaces of the upper and lower aft skins. The aft portion of the removable swept tip consists of additional upper and lower aft skin details, an additional core detail, a composite heel component and another metallic closure rib on the inboard end. The thickness of the inboard aft skins and the swept tip aft skins increase at the lap joint interface to provide sufficient bearing strength at the screw hole locations. Additional measures are required during the manufacturing process to seal this joint and limit the opportunity for water intrusion into the Nomex core due to the discontinuity of the aft skin structure.

The tip weight fitting for this design (**Option C**) is similar to the configuration used on **Option B**, the removable swept tip leading edge. It is tailored to facilitate the attachment of the swept tip assembly with screw fasteners along the attachment interface at 92% radius. The tip fitting is a single metal component that is installed into the outboard open end of the blade spar. It is retained with adhesive bonding to the inner surfaces of the upper and lower spar laminates. Ten mechanical fasteners that penetrate the spar laminates and fitting provide a failsafe load path. Flanges extend from the upper and lower sides of the outboard end of the fitting and extend beyond the outboard end of the spar. Nut plates are mounted on the inner surfaces of these flanges to retain the swept tip assembly. Access to the adjustable tip weight pockets in the weight fitting is gained by removal of the 36 screws that retain the swept tip assembly. As with design **Option B**, access to the adjustable tip weights from the end of the blade is the simplest option with the ability to remove the entire swept tip. This design option allows the swept tip assembly to be removed and replaced at the unit level – aviation unit maintenance (AVUM). This design option has a part count increase of 118 details and a weight increase of 10.5 lbs. per blade over and above **Option A**, the bonded swept tip design.

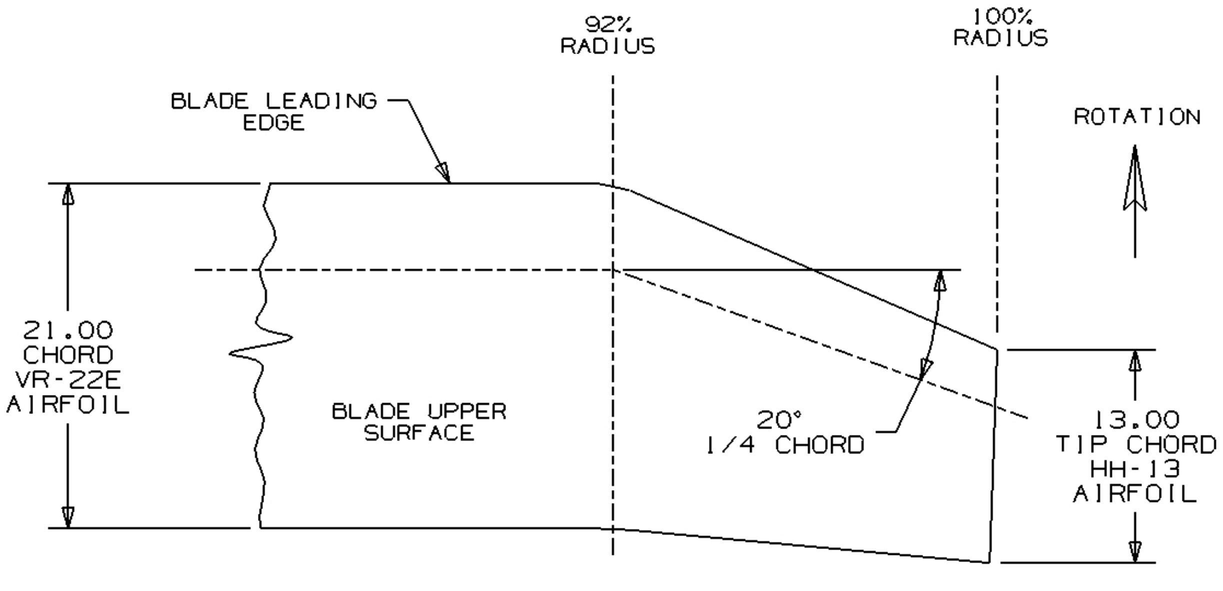


Figure 1
Plan View of Swept Tip Geometry
AARP M/R Blade

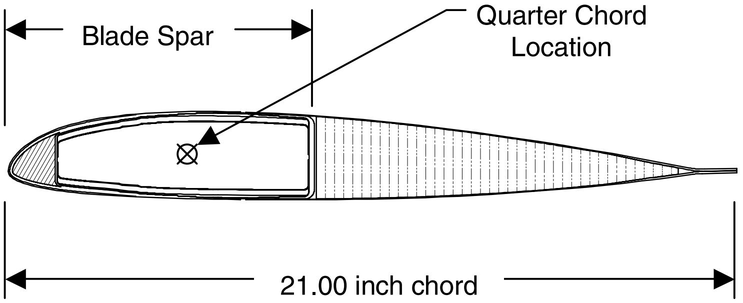


Figure 2a
Constant Blade Cross-Section
VR-22E Airfoil
Inboard of 92% rotor radius

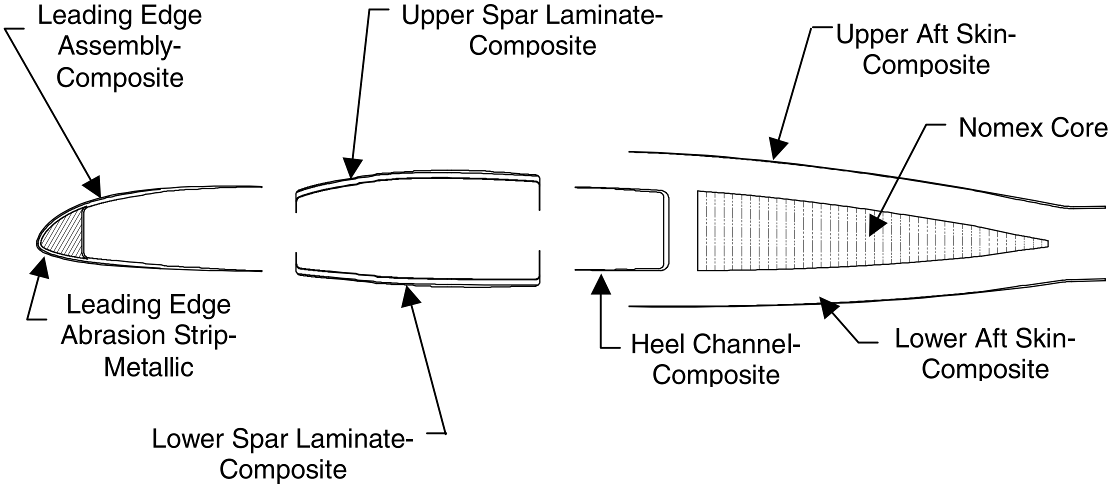
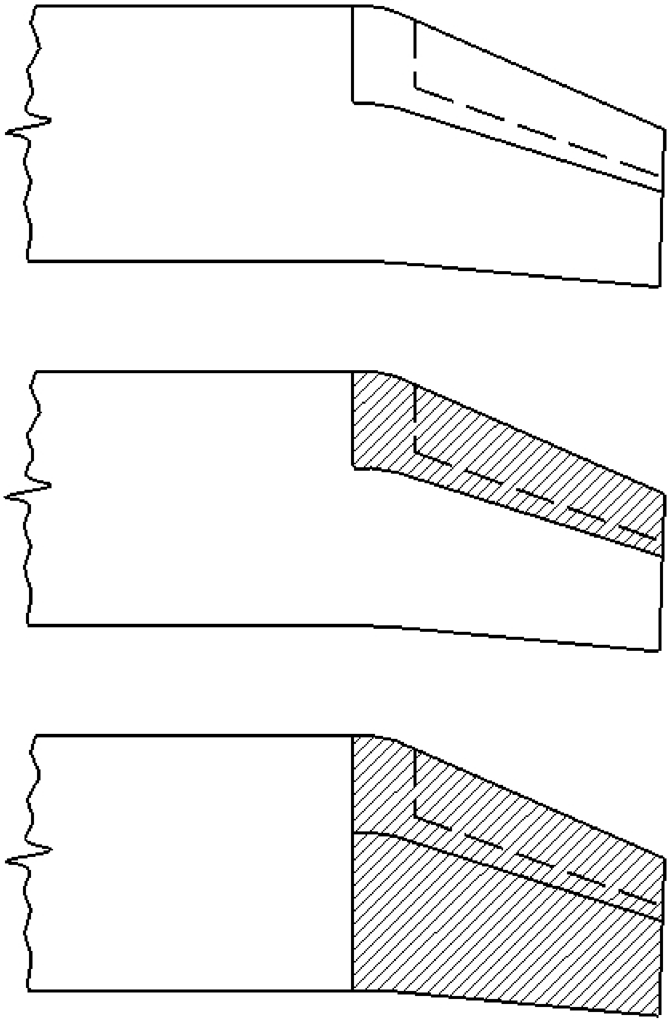


Figure 2b
Constant Blade Cross-Section
Exploded View
of sub-assembly components



Option A
Bonded Swept Tip
Leading Edge

Option B
Screw Fastened Retained
Swept Tip Leading Edge

Option C
Screw Fastened Retained
Swept Tip Assembly

Figure 3
Swept Tip Configuration Design Options

▨ Portion of swept tip that is removable with screw fasteners

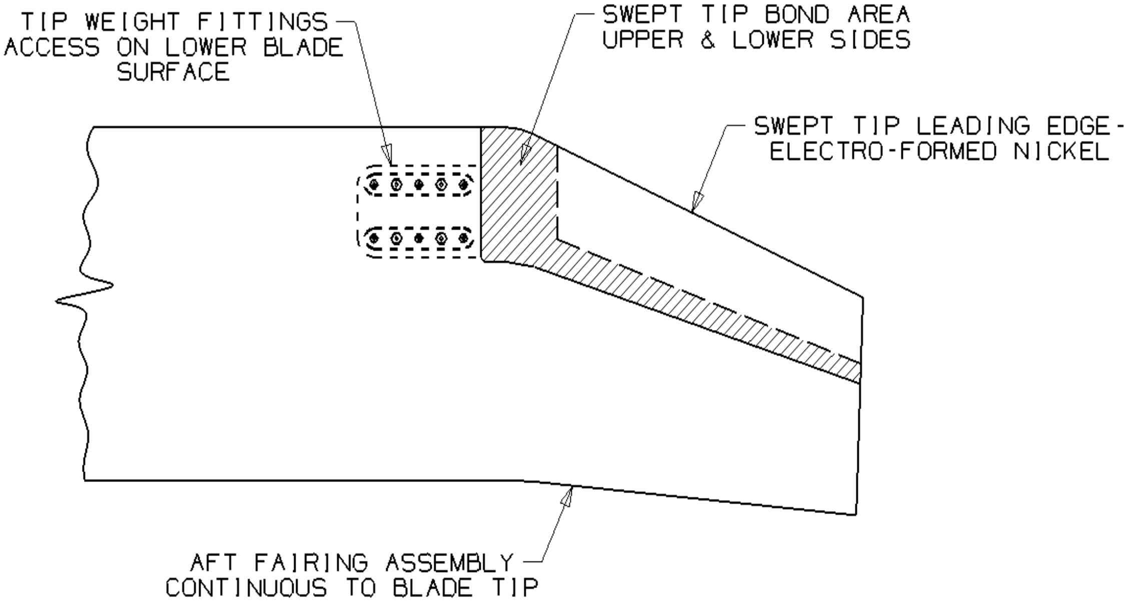


Figure 4

Option A

Bonded Swept Tip Leading Edge

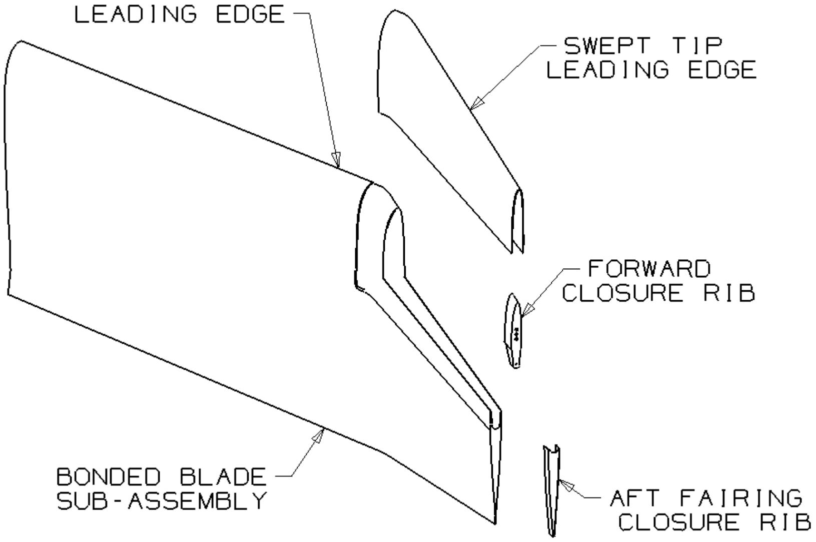


Figure 5

Option A

Bonded Swept Tip Leading Edge
Exploded view

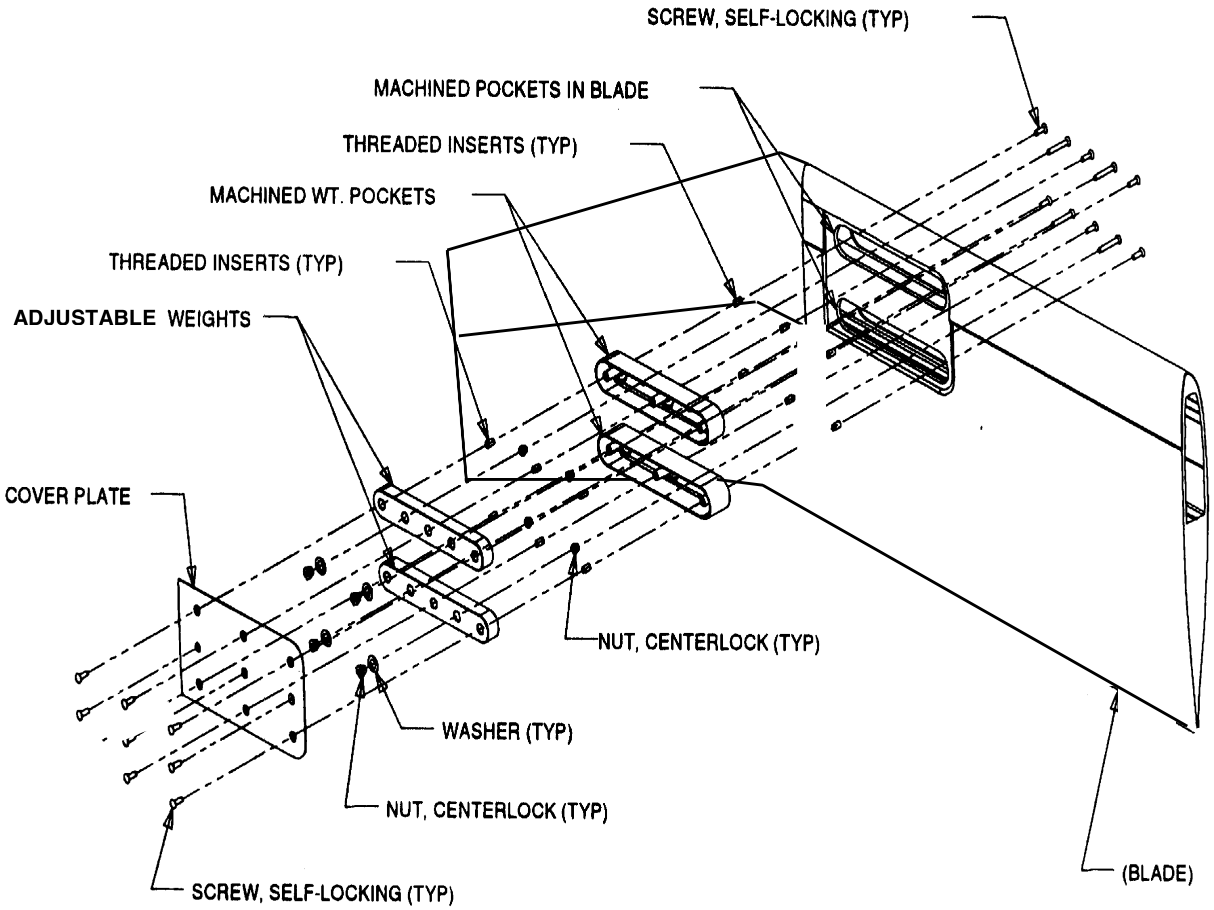


Figure 6

Option A

Bonded Swept Tip Leading Edge
Adjustable Tip Weight Configuration
Exploded View

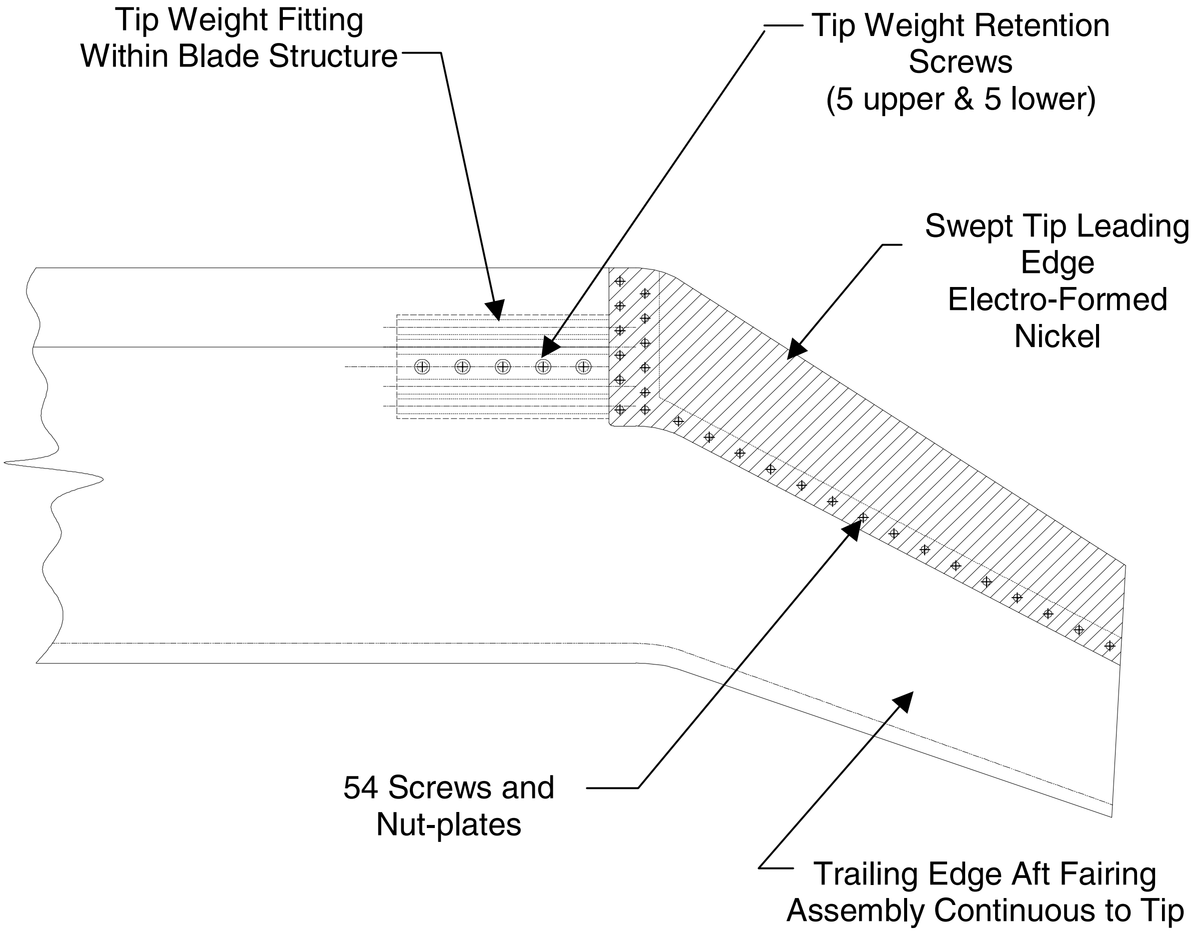


Figure 7

Option B

Screw Fastened Retained
Swept Tip Leading Edge

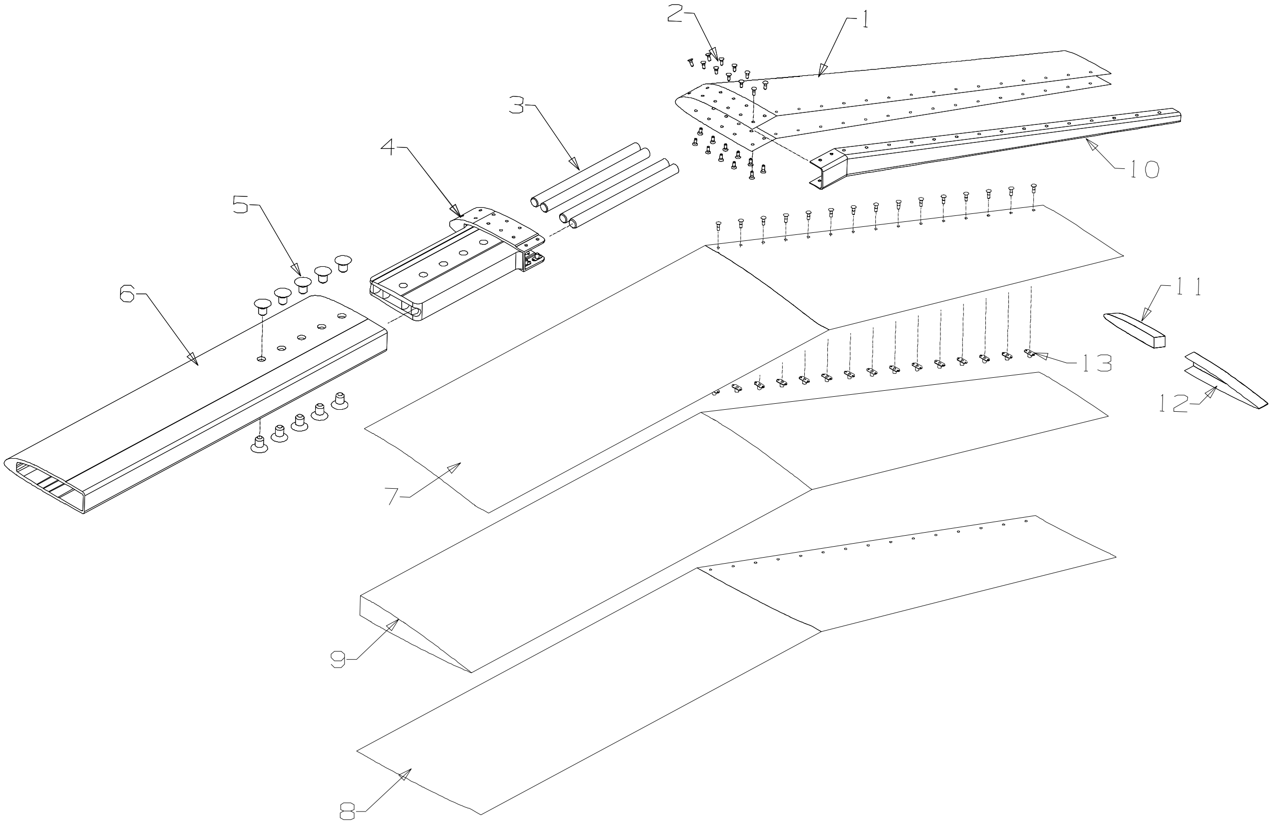


Figure 8
Option B
Screw Fastened Retained
Swept Tip Leading Edge
Exploded View

1 Swept Tip Leading Edge - Inconel
2 Retention Screws – 54 places
3 Adjustable Weights – 4 places
4 Tip Weight Fitting
5 Tip Weight Retention Screws
6 Composite Spar Structure
7 Upper-Aft Fairing Skin
8 Lower-Aft Fairing Skin
9 Aft Fairing Core - Nomex
10 Swept Tip Heel Channel - metallic
11 Swept Tip Leading Edge Closure Rib
12 Aft Fairing Core Closure Rib
13 Nut-plates – 54 places
(some nut-plates omitted for clarity)

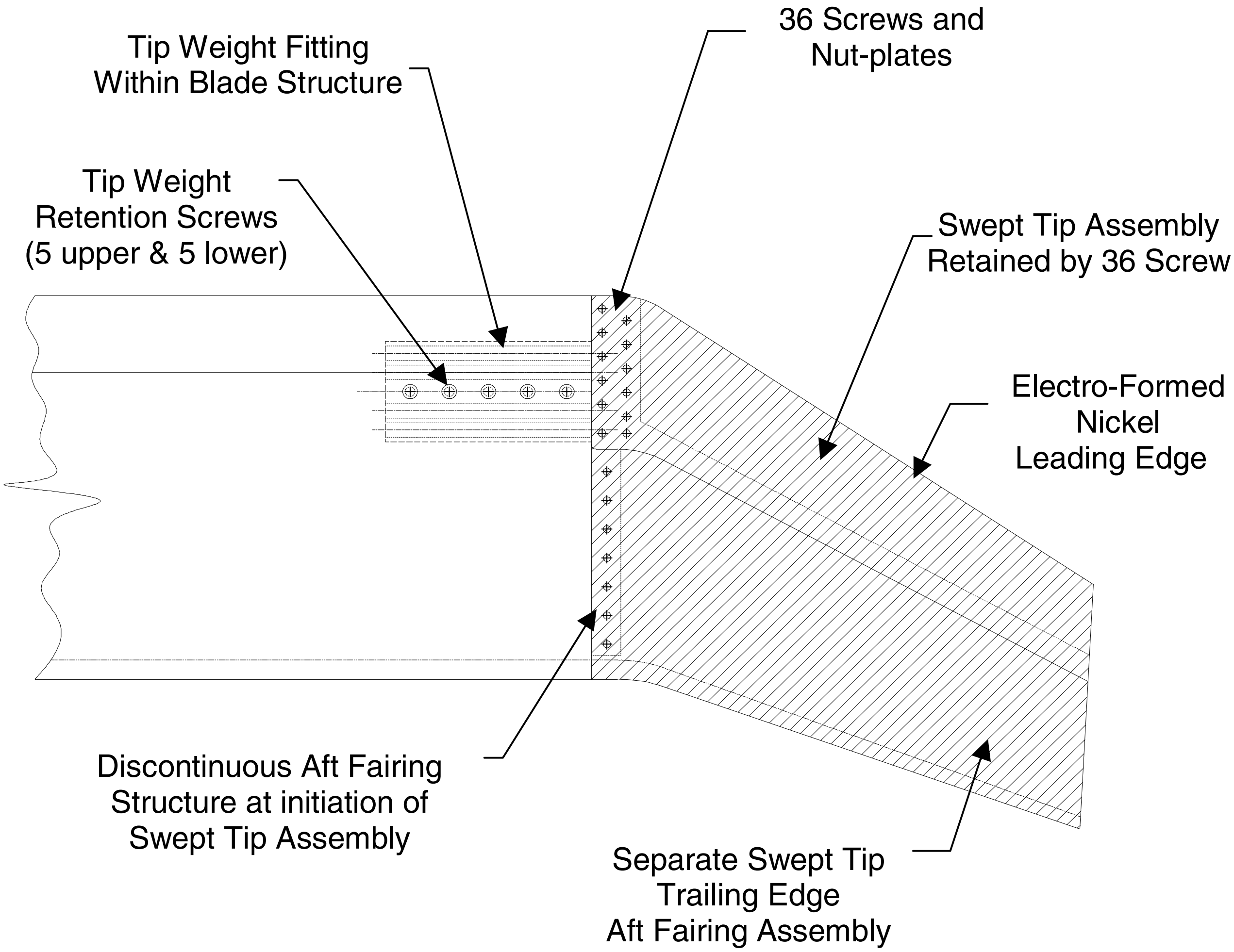


Figure 9

Option C

Screw Fastened Retained
Swept Tip Assembly

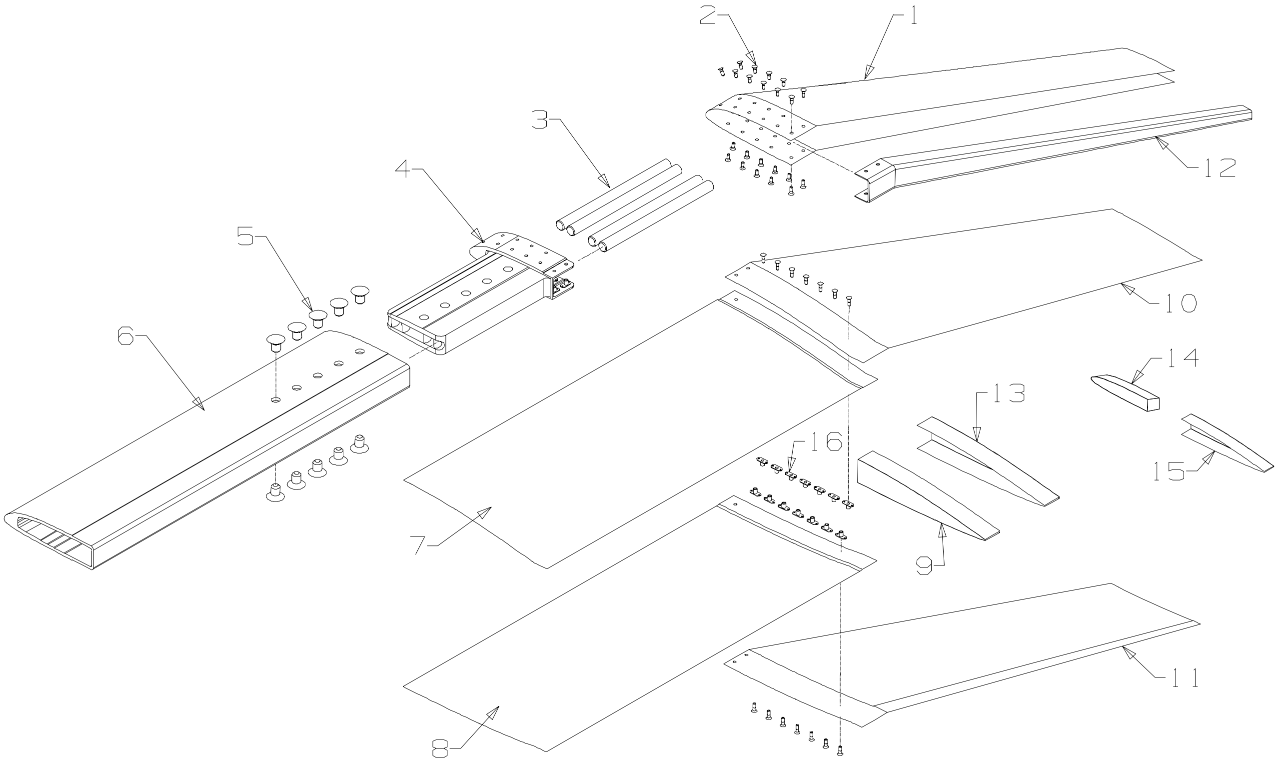


Figure 10

Option C

Screw Fastened Retained
Swept Tip Assembly
Exploded View

1	Swept Tip Leading Edge - Inconel	9	Aft Fairing Core Closure Rib
2	Retention Screws – 36 places	10	Swept Tip Upper Aft Skin
3	Adjustable Weights – 4 places	11	Swept Tip Lower Aft Skin
4	Tip Weight Fitting	12	Swept Tip Heel Channel - Composite
5	Tip Weight Retention Screws	13	Swept Tip Inboard Core Closure Rib
6	Composite Spar Structure	14	Swept Tip Leading Edge Closure Rib
7	Upper-Aft Fairing Skin	15	Swept Tip Outboard Core Closure Rib
8	Lower-Aft Fairing Skin	16	Nut-plates – 36 places

(Inboard and swept tip Nomex core details omitted for clarity)

MAIN ROTOR SWEPT TIP RELIABILITY

The current AH-64D Apache main rotor blade swept tip leading edge is a Line Replaceable Unit (LRU), which may be replaced at the unit level – aviation unit maintenance (AVUM). Form DA2410 data for January 1, 1990 through December 31, 1994 shows a Mean Time Between Chargeable Removal (MTBR) of 5850 blade hours for tip removals only. This value does not include entire blade removals where the tip may be damaged. This MTBR equates to approximately 68 tip removals at AVUM per year based on 100,000 aircraft flight hours per year for the AH-64 fleet and 4 tips per aircraft. The reasons for blade tip leading edge removal in percent of total reported removals for the current AH-64D Apache main rotor blade are shown in Figure 11 below.

A comparison of the design differences between the three proposed tip design options for the AARP blade and the current AH-64D swept tip leading edge design were used to predict how the removal rate of the swept tip will be affected. Each cause for removal was addressed individually and revised removal rates were predicted for each new design option.

The category that contributes to the highest rate of swept tip leading edge removals on the current Apache blade is ‘debonding’. A majority of this category is attributed to the debonding of the AM355 stainless steel spar channels of the constant blade section. The current blade has had a high rate of Spar #1 debonds at a location adjacent to the removable swept tip leading edge. The removal of the swept tip leading edge is required to evaluate and disposition these debonds. The elimination of the multiple metal spar channel design with the new AARP blade and the use of an improved film adhesive will eliminate the need to remove the swept tip due to debonding.

The next two categories that represent the second and third highest rate of swept tip removals on the current Apache blade are ‘wear’ due to erosion and ‘scheduled maintenance’. The erosion characteristics will be improved for all three proposed tip options with an increase to the thickness of the swept tip leading edge. The rate of tip removal due to maintenance will vary based on the design characteristic of each tip design option. If tip removal is required in order to perform maintenance tasks, the removal rate will be higher. One example in this category is the task of accessing the adjustable tip weight pockets. The bonded tip design (**Option A**) will have a lower rate in this category because tip removal is not required to access these weights. This design feature will also benefit the category of ‘screw problems’ by significantly reducing the total number of screws that require removal in order to gain access to the adjustable tip weights.

An anticipated reduction in the removal rates can be forecast for each design option proposed for the AARP blade swept tip. Each is based on a rational modification to the empirical removal rate data for the AH-64D blade tip. The removal rates for the three proposed tip options were calculated based on a reduction for each improved category. The removal rates for ‘disbonding’ were reduced by 2/3 for all three options with the elimination of the bonded multi-cell steel spar structure for the constant blade section. The removal rates for ‘wear’ were reduced by 20% for all three tip design options. This conservative reduction is based on the increased thickness of the swept tip leading edge for the proposed designs versus the current AH-64D. The removal rate for ‘scheduled maintenance’ was reduced by a ratio of 2/3 for the bonded swept tip leading edge design (**Option A**). This design option eliminates the need to remove any structure in the swept tip portion of the blade to access the adjustable tip weights. The removal rates for ‘screw problems’ for each design option was determined by a ratio of the number of screws relative to the AH-64D tip design. The categories for ‘fod/dents’, ‘cracks’, ‘other miscellaneous’, ‘twisted’ and ‘corrosion’ were not altered for the removal rate predictions for the three proposed designs since these items occur at a very low rate and are not projected to be significantly different for any of the proposed designs.

For this analysis, an increase usage rate of 125,000 aircraft flight hours per year for the AH-64 fleet is used. A total fleet of approximately 750 aircraft is also assumed. This yields an average of 167 flight hours per aircraft per year. The predicted MTBR for tip **Option A**, the bonded swept tip leading edge configuration, is 10,460 hours based on the methodology stated above. The predicted MTBR for tip **Option B**, the removable swept tip leading edge is 8200 hours. The predicted MTBR for tip **Option C**, the removable swept tip assembly is 8380 hours based on the same usage parameters. The rate for tip design **Option C** does not account for the potential for additional removals due to damage from water intrusion into the Nomex core.

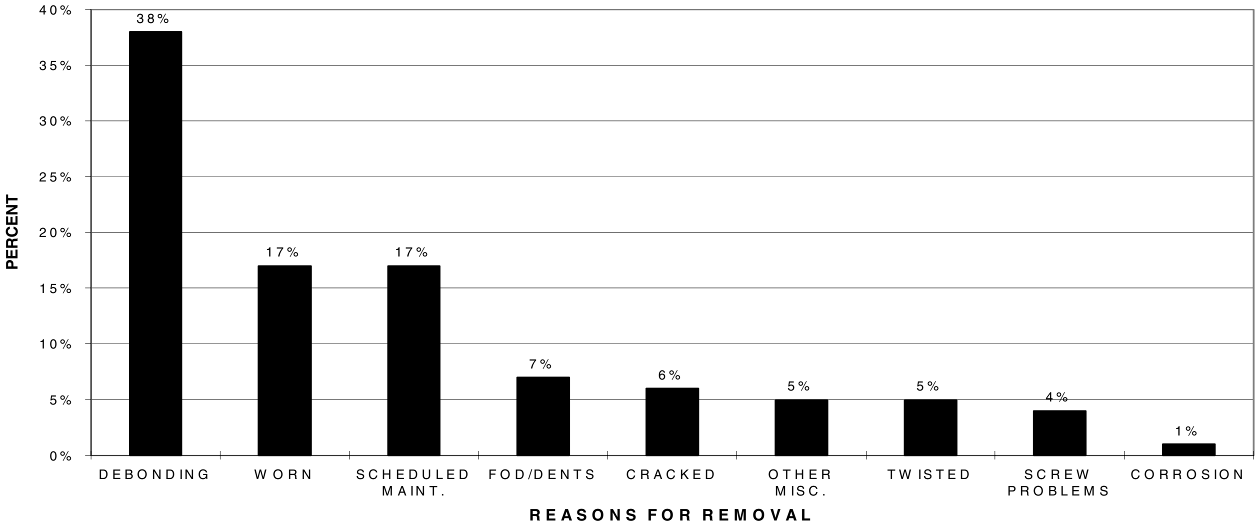


Figure 11

Current AH-64A/D
Main Rotor Blade Swept Tip
Removal Data

LIFE CYCLE COST ANALYSIS

A comprehensive bottoms-up cost analysis was performed for all three swept tip design options. The analysis includes estimates for the projected development, recurring labor and material costs, the cost for spare, repair and overhaul as well as total maintenance man-hours (MMH) for each design option. These estimates were used to predict the total life cycle cost (LCC) for each option. Table 1 below shows the total LCC for the three swept tip design options.

The development costs for each tip design option shown in Table 1 include the nonrecurring design, tooling and test efforts required to develop and validate each option. The development costs for Options B and C are greater than that for Option A, in part, because they require a separable, more complex assembly.

The total recurring hardware costs for each tip design option shown in Table 1 are derived from the projected unit production costs multiplied by the total number of 750 fielded aircraft and four blades per aircraft. The projected recurring production cost for Option A is $5697 per blade. This value, as well as the values for Option B and C were determined by a detailed manufacturing cost estimate that includes the recurring cost of the swept tip and associated hardware, tip specific labor and materials. The projected recurring cost per blade for Option B is $7,830 and for Option C is $9,383.

Table 1. Life Cycle Cost of Swept Tip Design Options

Life Cycle Cost ($M)	**Option A**	**Option B**	**Option C**
Development	$0.20	$0.54	$0.58
Recurring Hardware	$17.09	$23.49	$28.15
Spares, Repair & Overhaul	$5.98	$5.91	$9.38
MMH at AVUM	$1.78	$3.56	$3.48
Total LCC	$25.05	$33.50	$41.59

The spares, repair, and overhaul cost elements shown in Table 1 include the costs of all parts, components and labor (factory and depot only) that will be required for the removal and replacement of the swept tip for each design option. Estimates are based on the predicted MTBR for each design option over a 20 year time period after initial fielding. The projected swept tip unit replacement cost for Option A is $4050. This includes the replacement cost of the swept tip detail only. For this analysis, the repair and replacement of swept tip Option A is accomplished only at the depot level. The labor costs for this option is based on an estimate of 18.0 hours to remove and replace the Option A swept tip leading edge and is billed at $120 per hour. The projected swept tip unit replacement cost for Option B is $4833 and for Option C is $7840. This includes the replacement cost of the swept tip details only. It is assumed that Options B and C repairs and replacement will be accomplished at the unit level. The labor cost for removal and replacement of these two options is captured in the MMH. The calculations for spares cost for each swept tip design option are shown in Table 2.

The maintenance man-hours (MMH) costs shown in Table 1 include the costs of all unit level labor required for on condition maintenance of the swept tip for each design option. The design configuration of the swept tip will impact the total predicted cost for MMH at AVUM. The maintenance man-hours per flight hour (MMH/FH) for the swept tip **Option A** is projected to be .0022. Removal and replacement of the swept tip detail will be performed at the depot level for **Option A** after the affected blade has been removed at AVUM. As a result, the overhaul cost for **Option A** is impacted and only the blade removal and replacement time is used to calculate MMH/FM for this design option. The MMH/FH for swept tip **Option B** and **Option C** are projected to be .0044 and .43 respectively. The MMH/FH values for **Option B** and **C** are greater then that of **Option A** due to the added time required to remove and replace the swept tip detail at AVUM once the blade has been removed from the aircraft as well as the lower MTBR's for these options. The calculation of MMH/FH for the three tip options is shown below in Table 3.

The unit-level maintenance labor rate is assumed to be $81 per hour. The discard rate for removed tips for all three options is assumed to be 100%. The MMH contribution to LCC for each option are shown below in Table 4.

Table 2. Spares, Repair & Overhaul Cost Calculation

	(a)	*(b)*	*(c)*	*(d)*	*(e)*	*(f)*	*(a*4/b)*(c+d)*e*f*
Option	*FH/AC-Yr*	*MTBR*	*Parts$/Removal*	*Depot Labor*	*Quantity*	*Years*	*Spares Cost ($M)*
A	167	10460	$4,050	$2160	748	20	$5.98
B	167	8200	$4,833	---	748	20	$5.91
C	167	8380	$7,840	---	748	20	$9.38

The following is a sample calculation for **Option A**:
(167 FH/AC-Year)(4 Tips/AC)(1 Removal/ 10460 Tip Hrs) * ($4050 + $2160)/ Removal * 748 AC * 20 Years = $5.98M

Table 3. Maintenance Man-Hours / Flight Hour Calculation

	(a)	*(b)*	*(c)*	*(a+b)*4/c*
Option	*Blade removal and replacement time (Man-Hrs)*	*Swept Tip removal and replacement time (Man-Hrs)*	*MTBR*	*MMH/FH*
A	5.7	-	10460	.0022
B	5.7	3.4	8200	.0044
C	5.7	3.4	8380	.0043

Table 4. Maintenance Man-Hours Cost Calculation

	(a)	*(b)*	*(c)*	*(d)*	*(e)*	*4*a*b*c*d*e*
Option	*MMH/FH*	*FH*	*Quantity*	*Labor Rate*	*Years*	*MMH ($M)*
A	0.0022	167	748	$81	20	$1.78
B	0.0044	167	748	$81	20	$3.56
C	0.0043	167	748	$81	20	$3.48

UNIT LEVEL COST IMPACT

The unit level cost for each swept tip design is a function of the replacement cost of the swept tip detail and MTBR for each. This cost can be put in terms of swept tip maintenance cost per aircraft per year. Currently, if the unit is required to send an entire blade to the depot level for repair, the unit is issued a replacement blade and charged the full acquisition cost of the replacement blade minus a turn-in credit for the repairable blade. Since the entire blade would be returned to depot in order to replace the Option A swept tip, the apparent cost to the unit per tip replacement will be higher than that of Options B or C. The unit level cost for replacing a single swept tip for Options B or C would be the unit replacement cost of the removable swept tip detail. In the case of design Option A, the replacement cost would be the cost of the AARP main rotor blade minus the turn in credit rate. Although this results in an apparent cost disadvantage for swept tip Option A at the unit level, the impact would be only temporary until unit budgets were readjusted for new Army cost factors. The absolute cost difference for the unit level between the three design options will be on the order of hundreds of dollars per aircraft per year. Due to this small magnitude in difference, unit level cost is not a significant factor in the selection of the swept tip design for the AARP.

SYSTEM IMPACT ON AH-64D APACHE LONGBOW

The root end attachment geometry of the new AARP blade is designed to be common with the current AH-64D blade. This feature will allow the use of the AARP blades on the current Longbow helicopter without additional modifications to the hub or airframe structures.

The aerodynamic performance of the AH-64D Longbow helicopter will benefit with the use of the AARP rotor blades installed. A design constraint for the new AARP blades is to not exceed the structural capability or adversely affect the operational performance of the aircraft. This requirement sets a constraint on the weight of the AARP blade design. If the weight of the AARP blade exceeds 162 pounds, whirl mode stability concerns will likely preclude using these blades without significant modification to the aircraft at other locations. Swept tip Option A provides the lowest blade weight of solution with the least risk of producing adverse conditions.

Increased blade weight will result in increased centrifugal force (CF) when the blades are rotating. Higher CF from the blades can result in degradation to the structural life of the Longbow main rotor hub strap pack. A heavier AARP rotor system will also result in less flight performance improvement of the aircraft with the new blades. This is counter to the design goal of maximizing the flight performance without impacting the cost of the AARP main rotor blades.

DESIGN COMPARISON

The significant characteristics of the three proposed swept tip design options for the AARP main rotor blade are summarized in Table 5. The bonded swept tip leading edge design (Option A) provides the lightest configuration due to a minimum of structure within the blade in the aft sweeping portion of the tip. It also minimizes the probability of water intrusion into the blade structure with the elimination of mechanically fastened joints to secure the swept tip. The removable leading edge swept tip design (Option B) only allows the forward portion of the swept blade tip to be easily replaceable with mechanical fasteners. This feature allows for the replacement of the tip leading edge due to damage and erosion but does not accommodate the replacement of the trailing edge structure. The entire removable swept tip assembly design (Option C) offers the greatest versatility for blade tip removal and replacement due to damage and erosion to either the leading or trailing edges. Tip design Option C requires more structure at the mechanical connection than the other two swept tip design options and in turn weighs more. Higher blade weight poses an increase risk of adverse structural and dynamic affects on the Longbow aircraft.

The bonded swept tip design (Option A) offers the greatest potential for outer mold line (OML) contour consistency in the swept tip region of the blade. This will be provided by an accurate and repeatable method of positioning the swept tip detail during the installation and bonding process. With tip design Options B and C, there exists the potential for OML contour distortion and/or mis-location of the swept tip structure. This is due to the attachment with mechanical fasteners when the screws are either over or under tightened. Distortion of the OML may also occur if there exists a contour deviation between the swept tip and the interfacing blade structure. The result of tip OML contour distortion or mis-location may include difficulty achieving acceptable blade track and balance as well as increased vibration levels.

Table 5. Summary of Swept Tip Design Characteristic

	Option A	**Option B**	**Option C**
Appox. Blade Weight – lbs.	155	164	166
Parts Count- Swept Tip & Tip Weights	56	203	174
Recurring Cost of Tip ($/Blade)	$5,697	$7,830	$9,383
Total Life Cycle Cost (20 Years-FY-00$M)	$25.05	$33.50	$41.59
Projected MTBR – (Blade hrs)	10,460	8,200	8,380

CONCLUSION

A comprehensive economic analysis of the swept tip design options indicates that the bonded swept tip design (Option A) will have the lowest total life cycle cost of the three swept tip design options presented. The alternate tip designs (Options B & C) provide the ability for tip replacement at AVUM but will add significant penalties to the acquisition cost. Option A and B have similar costs for spares, repair and overhaul over the life of the blades but Option A provides lower maintenance costs. The results of this analysis indicate a temporary cost disadvantage for swept tip Option A to the unit level budget. However, this impact is insignificant compared with the substantial life cycle cost (LCC) benefit of Option A. The analysis indicates that there is no economic benefit for a removable swept tip capability. This is primarily due to the high recurring production cost for the removable swept tip options with no significant economic benefit to the Army once the blades have been fielded.

The Boeing Helicopter AARP IPT Design Team selected the bonded blade swept tip construction (Option A) for the AARP main rotor blade design. The bonded swept tip leading edge will produce the lowest life cycle cost and system weight for the new Longbow Apache main rotor blade. The use of this design contributed to Boeing's ability to meet the acquisition cost and system performance goals for the AARP program while fulfilling the operational requirements of the AH-64D Longbow helicopter.

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