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An Assessment of Propeller Aircraft Noise Reduction Technology

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1.0 INTRODUCTION

Propeller aircraft noise reduction has been studied since the early days of aviation, Initially the need for noise reduction was coupled to the need for reduced detectability in military operations, As the number of airplanes increased and their size and horsepower increased there was a need to reduce their noise because of annoyance to the residents near airports or near areas where there were significant numbers of overflights. In Europe where there is a higher population density and a quiet living environment is considered highly desirable, there is more need for propeller aircraft noise reduction than in the America's where there is more open space and higher noise levels in the environment are accepted. This level of acceptance, however, is deteriorating, particularly near the National Parks where the noise of tourist flights degrade the isolated nature of the environment that the park visitors desire. Also, the General Aviation airplane market that has deteriorated for more than 10 years is beginning to recover. This recovery will increase the number of airplanes and therefore, unless noise is reduced, the annoyance caused by these airplanes will increase.

This report is an assessment of the current state-of-the-art of propeller aircraft noise reduction technology. It consists of: (1) an assessment of the probable potential noise reduction gains that might be achieved, and (2) a review of past and current propeller aircraft noise reduction research programs to determine their acceptability.

In assessing the noise reduction concepts, cost and manufacturability is considered. In particular, the technology that can be applied to existing propeller driven airplanes is evaluated. Since piston engine noise is known to be a factor in aircraft noise (when the propeller noise is reduced), this report also includes a review of engine noise reduction concepts.

In reviewing the literature, it was not possible to review all of the noise reduction work that has been reported in the past 65 years. It is hoped that the reports reviewed will provide sufficient information to assess the potential for practical methods to satisfy noise reduction needs for the future.

The report is organized into the following sections:

2.0 PROPELLER AND PROPELLER AIRCRAFT NOISE REDUCTION LITERATURE REVIEW

In this section the important results from various propeller noise reduction analyses and tests are reviewed. It should be noted that experimental programs that relied on static tests have not been included as these results are not a reliable indicator of flight test results. Also the literature on the Prop-Fan, the multiblade advanced high cruise speed turboprop is not included as its geometry (very high power absorption, relatively small diameter, wide chord, highly swept planform, many blades) is quite inconsistent with the geometry of the propellers in current use or likely to be in wide spread use in the near future.

It should also be noted that some of the experimental programs made use of engine mufflers. Where they were used, they are discussed in the context of the airplane noise reduction. Some of these mufflers are discussed in reviews of separate reports in section 3.0 of this report.

Vogeley, 1948 - This report[2.1] describes the noise reduction achieved by changing the number of blades and RPM of the propeller on a high wing reconnaissance airplane. Engine exhaust muffling is also used. This was a modification of a Stinson L-5 liaison type airplane selected as being representative of personal type airplanes in the 150 to 200 horsepower class. Although the experiments were conducted with a military reconnaissance airplane, it appears that the motivation for this work was the reduction of noise around general aviation airports. Table 2.1 lists the characteristics of the standard and modified aircraft. The most obvious change is shown in Fig. 2.1. Here are the two relatively narrow blades are seen to have been replaced by five paddle type blades. As Table 2.1 shows, the propeller of the standard aircraft was directly driven off the engine while the propeller of the modified aircraft was gear driven. Also the engine exhaust noise was reduced by use of a tuned chamber muffler. The remarkable reduction in noise of this modification is shown in Fig. 2.2 where it can be seen that as much as 20 dB reduction was achieved. Even more impressive is the comparison of the noise of the modified airplane with power on and power off shown in Figure. 2.2. The aircraft with power on is seen to be only 5 dB noisier with power on than it is with power off. The propeller noise reduction was so effective that the airframe noise of this small aircraft was a significant factor in the total aircraft noise. Performance of this installation was claimed to be as good or better than the standard aircraft, but the weight penalty was not acceptable.

With respect to the above mentioned weight penalty, Vogeley states that "the five-blade propeller as tested, was very heavy but only because the hub was designed for wind-tunnel work and no consideration had been given to weight. Actually, the wooden blades each weigh only 6 pounds and it is estimated that, if a complete wooden propeller had been built, the total weight would have been less than 50 pounds as compared with approximately 25 pounds for the two-blade propeller.

The modified airplane included an exhaust muffler of the "acoustical-filter-type". From Vogeley's description this was fairly large and was not optimized from a size and weight standpoint. In use it appeared to be mounted aft of the pilot's compartment inside the fuselage with the exhaust pipe from the engine to the muffler outside the fuselage. The exhaust from the muffler exited the upper surface of the fuselage near the leading edge of the vertical stabilizer. Test stand results showed the maximum noise at 300 ft for the engine without muffler operating at full throttle at 2790 RPM to be 89 dB (unweighted). With the muffler installed the level was 67 dB (unweighted). Some tests done during the program indicated that the valves, gears and intake noise in the muffled engine could have been dominant,

Beranek, et al. 1950 - In this report [2.2] the effect on flyover noise of reducing propeller RPM and changing the propeller design (particularly the number of blades) is evaluated experimentally. Tests were conducted on two airplanes, standard and modified versions of a Stinson Voyager 165 shown in Figure 2.3 and a Piper Cub J-3 shown in Figure 2.4.

Tests were conducted statically on the ground, and at takeoff and flyover. Data is reported in unweighted and weighted dB. The data of most interest was obtained during 500 ft flyovers and reported in dB with a 40 dB weighting. This weighting is shown in Figure 2.5 along with the A-Weighting currently used in General Aviation noise certification. Because of the similarities of these two weightings, the results of the reported tests are a good indication of the certification noise benefits of reducing RPM and changing number of blades.

The standard Stinson was a 1948 Voyager 165 equipped with a Franklin six-cylinder direct drive engine rated at 165 hp at 2800 RPM. The modified Stinson was a 1946 Stinson Voyager 150 equipped with an experimental geared Franklin engine rated at 180 hp at 3050 RPM. This engine had a planetary gearbox with a gear ratio of 0.632 to 1. The exhaust system of the modified Stinson had two Maxim silencers installed. Each muffler weighed 12 pounds with supporting brackets weighing 2.5 pounds. The back pressure of the mufflers as measured at 2900 RPM at full throttle was 4 inches of Hg.

The standard Piper Cub J-3 shown in the upper photograph of Figure 2.4 was equipped with a Continental four-cylinder direct-drive engine rated at 65 hp at 2300 RPM. The modified Cub shown in the lower photograph of Figure 2.4 is essentially the same as a standard configuration except for a new larger vertical fin and rudder. The engine in this airplane is a Lycoming four-cylinder, direct-drive rated at 108 hp at 2600 RPM. It was modified with a belt drive to reduce propeller RPM. The exhaust noise was reduced by an ejector system that fed into a perforated tube lined with a bulk absorber material. This system also kept engine temperatures at an acceptable level for all tests. The ejector system weighed 9 pounds and caused a back pressure of 10 inches of Hg at 2500 RPM at full throttle.

Figure 2.6 shows the time history of the maximum power 500 ft flyover noise for the Stinson airplane with the different propeller and engine configurations. All of the experimental configurations show a dramatic reduction in maximum flyover noise relative to noise of the standard configuration (configuration 1). The peak levels from Figure 2.6 are listed in Table 2.2 along with the geometry of the configurations. Photographs of the propeller tested are shown in Figure 2.7. Also in Table 2.2, the information on a standard and modified Piper Cub are listed. The photographs of these configurations are shown in Figure 2.4.

All of the experimental configurations show a reduction in noise relative to the standard configurations. The table shows the following:

1. The Stinson geared 2 blade configuration shows a reduction of 11 dB.

2. Additional reductions can be seen as number of blades increases.

3. Three of the four propellers with four blades show similar levels when operated at the higher power level. One four blade configuration (2H) shows a level 3 dB higher than configurations 2F or 2G at the lower power level. The reason for this is not discussed.

4. The modified Cub is 9 dB lower in level than the standard Cub.

The performance penalties in cruise for the different configurations is not discussed. The penalties in takeoff run are listed in Table 2.2. Some penalties exist in the modified configurations but it is not clear whether these penalizes would exist of variable pitch was included in the modified configurations.

Roberts and Beranek, 1952 - In this report[2.3] various propeller configurations were tested to reduce noise on the pusher-type amphibian airplane shown at the top of Figure 2.8. The results were compared with those obtained in an earlier program on the tractor installation shown at the bottom of Figure 2.8. Most of the data on the amphibian was obtained with a geared engine. However, a reference case with a direct drive engine is included.

Extensive flight and ground static tests were conducted. An indication of the potential noise reduction of the various configurations can be seen by reviewing maximum measured levels of the maximum power flyover noise at an altitude of 500 ft. The data of most interest is that which was acquired using the 40 dB weighting filter. This filter characteristic is the same used in the earlier tractor airplane test series described above. The similarity of the A-Weighting and 40 dB weighting characteristics allows the results of these early tests to be used as an indication of the A-Weighting noise reduction potential of the various configurations.

The results of the tests are summarized in Table 2.3. The propeller configurations are shown in Figures 2.9 and 2.10. All pertinent parameters are included. Note that most of the pusher tests used a muffler on the engine. This is shown in Figure 2.11. Configurations 9A, 9B, 9C, and 9D positioned the muffler immediately above the engine so the exhaust gases passed through the area swept out by the propeller. In configuration 10 the muffler was moved close to the fuselage so the exhaust would not pass through the area swept out by the propeller.

The propellers were operated in three ways regarding the blade pitch. Where "solid propellers" (no pitch variation capability) were used, only one pitch angle was possible at takeoff and flyover. The standard pusher (configuration 6) uses a propeller that automatically changes pitch. The other test configurations (8, 9A, 9B, 9C, 9D and 10) were run with one pitch angle for takeoff and a second pitch angle for the high speed flyovers. This is equivalent to a system that would automatically change pitch for different operating conditions.

The noise levels (40 dB weighting) of Table 2.3 show the following:

a. The standard tractor (Configuration 1) is 11 dB noisier than the standard pusher (Configuration 6). The reason for this is not known. However, the shielding of the pusher installation by the fuselage and wing and the variable pitch of the standard pusher may hold the explanation. Also, interaction of the engine pylon wake with the propeller could be another explanation.

b. The modified pusher with a geared engine and a 4-blade propeller set to simulate variable pitch (2 fixed pitch settings) is 2.5 dB lower in level than the fixed pitch 4 blade propeller on the direct drive engine. This is probably due to the reduction in tip speed from 815 ft/sec to 537 ft/sec.

c. With the geared engine the lowest noise was achieved with a 4-blade simulated variable pitch propeller with a muffler installed on the engine. This level was 4.5 dB lower than the same propeller and engine without the muffler. It was 9.5 dB lower in level than the direct drive 2 blade variable pitch configuration.

d. The weight impact of the various beneficial changes were:

   1. an added 97 pounds of changing from a fixed pitch 2 blade propeller on direct drive engine to a 4-blade variable pitch propeller on a geared drive engine;
   2. an increase of 17 pounds for a muffler;
   3. a change of about 4 dB/blade to 7 dB/blade as number of blades increased up to 4 blades. Further increase in number of blades increased the noise.

e. In general, the maximum level flight speed and average takeoff run before liftoff were similar for the different propeller and engine combinations except for the solid fixed pitch propeller or the direct drive engine where the takeoff run increased substantially. It appears that satisfactorily performance coupled with reduced noise requires a variable pitch propeller.

The variation in weight impact of adding blades which was described in item 3 above deserves further discussion. It appears that the experimental blades were not designed as a family but instead were in some cases commercial propellers (e.g. configuration 6) and in other cases experimental propellers (e.g. configurations 9C and 9D). In general, as the number of blades increases, the blade chord decreases up to point where structural problems are created by the desire for all the blades to retain the same maximum airfoil thickness divided by chord. This thickness ratio is needed to retain aerodynamic performance. It can be seen in figures 2.9 and 2.10 that there is considerable difference in the blade designs for the propellers tested. Therefore it is not surprising that the weight per blade varied from 1 to 7 pounds per blade.

Figure 2.12 is an example of the time history of the 500 ft max power flyover of the standard tractor and standard pusher with 2 blade propellers. It can be seen that the maximum level of the tractor propeller exceeds that of the pusher. However the pusher remains high in level before and after the peak. The pusher characteristic was found for all of the configurations tried (see Figure 2.13). The pusher noise characteristics as also considered more objectionable than the tractor. In the light of more recent research on propeller noise, this more objectionable characteristic is undoubtedly due to the interaction of the wake from the engine support pylon with the propeller.

<u>Johnston and Law, 1957-1958</u> - These reports [2.4,2.5] summarize a program similar to that reported by Vogeley[2.1]. However the objective of this work was to reduce detectability in a military mission. The characteristics of the standard and modified Otter used in this program are listed in Table 2.4. The similarity to the approach taken in the Stinson L-5 modification of reference 2.1 can be seen in Table 2.4 and in the photographs of the standard and modified aircraft of Fig. 2.14. A sample of the noise data from this program shown in Fig. 2.15 indicates that the propeller noise for the Otter has (like that of the L-5) been reduced to a level close to the airframe noise. This once again demonstrates the beneficial effect of increasing number of blades and lowering rpm and tip speed on noise level. Also in the case of the Otter, the mechanical gearbox noise is seen in Fig. 2.15 to contribute at higher frequencies.

<u>Hoffman and Muhlbauer, 1974</u> - These two papers[2.6,2.7] appear almost identical and describe noise reduction concepts that the authors consider practical for General Aviation airplanes. A basic suggestion is reduction in tip speed by reduced diameter at a given RPM or by reducing propeller RPM with a gearbox on the engine. They endorse the idea of increasing propeller performance to allow reducing diameter and also reducing airplane drag so the propeller thrust required can be reduced. In their opinion even propeller RPM as low as 2000 may not be sufficient to reach future noise requirements.

In terms of future requirements the authors state that "if a 65 dB (level flyover) propeller noise level is to be achieved, it will be necessary to use engines with gearboxes. The development of three blade propellers must be extended to the order of magnitude 130 to 300 hp, and four blade propellers for the 300 to 500 hp output range must be developed."

<u>Harlamert, 1974</u> - The development of a five-blade propeller to reduce noise pollution is

discussed in this report[2.8]. This propeller was developed for use on relatively high horsepower turbine engines at low propeller RPM. A performance tradeoff study showed that acceptable takeoff and cruise performance could be achieved with a 5 blade propeller. The use of supercritical airfoil sections is suggested for the tip region of a propeller to allow the blade chord to be reduced. Noise benefits are mentioned for the use of round or elliptical tip shape rather than a square tip shape.

Dingeldein/Hilton/Conner, 1975 - In this series of five reports[2.9-2.13], an evaluation of the noise reduction potential for five airplanes is evaluated. The objective of this noise reduction was reduced detectability for military applications. Thus the information is only generally applicable to certification.

The aircraft characteristics are listed in Table 2.5. The 0-1 and U-10 are high wing airplanes very similar to typical General Aviation airplanes. The 0-2 is fairly large twin engine airplane of the General Aviation type but with an unusual powerplant configuration. One powerplant is mounted in the nose and the second is mounted as a pusher behind the cabin. The OV-1 is a twin turboprop which does not have a civilian counterpart. It is of interest as there are twin turboprop civilian airplanes where noise reduction features found practical in the OV-1 could be applied. The A-6 is a twin turbojet so it will not be discussed further as it is beyond the scope of the present report.

For each of the airplanes described above and in Table 2.5 the flyover noise of the unmodified airplane was measured. This was then used as a reference for calculating the reduced noise level that might be achieved by changes in the engine and propeller.

For the 0-1 the modifications are summarized in Table 2.6. The associated performance is summarized in Table 2.7. . The approximate A-Weighted levels for these configurations are follows:

> 78 dB for the unmodified configuration, 69.5 dB for Mod. I, 62 dB for Mod. II, and 56.5 dB for Mod. III.

As shown in Table 2.6, the unmodified 0-1 had a 2 blade fixed pitch propeller on a direct drive engine. Mod. I retained the direct drive engine but used a 6 blade reduced diameter controllable pitch propeller and an external muffler. Table 2.6 shows that Mod. II used a geared engine with a large diameter 5 blade controllable pitch propeller and a muffler mounted inside the fuselage aft of the passenger compartment. Table 2.6 shows that Mod. III used an engine geared to reduce propeller RPM even lower than Mod. II. Mod. III used a 5 blade controllable pitch propeller of higher solidity than Mod. II. Mod. III included a very large (6.15 ft^3) internally mounted muffler.

The performance and weight impact of the different modifications can be seen in Table 2.7. The impact of Mod. I on weight and performance appears quite acceptable. It is believed that the cost of a muffler and 6 blade controllable pitch propeller would be significant. The Mod. II impact on performance and a weighted would probably be acceptable but there may be a further cost for a geared engine. The Mod. III impact on performance and weight is quite significant and would probably not be acceptable.

For the U10, the modifications are summarized in Table 2.8. The associated performance is summarized in Table 2.9. Note that the unmodified configuration has a geared engine. Mod. I changes the propeller to 5 blades and adds a muffler. Table 2.9 shows that the impact on weight and performance appears acceptable. However cost would be a factor in assessing whether the noise benefit is worthwhile. Mod. II changes the engine gear ratio and increases the diameter of the 5 blade propeller. The muffler of Mod. II is retained. The approximate A-Weighted levels for these configurations are as follows:

85.5 dB for the unmodified configuration, 82 dB for Mod. I, and 74 dB for Mod. II.

Again, the weight and performance impact appear acceptable but the cost impact would be a consideration.

For the 0-2 the modifications are summarized in Table 2.10. The associated performance is summarized in Table 2.11. The unmodified configuration has a 2-blade propeller mounted on a direct drive engine. Mod. IA and IB changes the propeller to 6 blades with a reduced diameter. Both Mod. IA and IB include mufflers; that of IB is larger than IA. Table 2.11 shows that the impact on weight is not significant but there is some impact on performance that may or may not be acceptable. Mod. II uses a geared engine with a 6 blade propeller the same diameter as the unmodified 0-2. There is further degradation in performance and weight that may not be acceptable.

The approximate A-Weighted levels for these configurations are as follows:

81 dB for the unmodified configuration, 77.5 dB for Mod. IA and Mod. IB, and 75 dB for Mod. II.

As in the other airplanes discussed previously, there is a weight and cost associated with more blades, a muffler, and a geared engine.

For the OV-1 the modifications are summarized in Table 2.12. The associated performance is summarized in Table 2.13. This is a turbine powered aircraft where engine muffling was not considered in the study. The octave band noise levels for the various modifications are shown in Figure 2.16 It can be seen that the high frequency noise is not significantly reduced by the propeller changes. This is because this part of the noise spectrum is engine noise controlled. The approximate A-Weighted levels for the various configurations shown in Figure 2.16 are as follows:

82.8 dB for the unmodified airplane, 80.7 dB for Mod. I, 77.5 dB for Mod. II, and 74.4 for Mod. III.

Mod. I uses a 5 blade smaller diameter propeller on the existing engine. Mod. II changes the gear ratio on the engine to reduce the tip speed with a 5 blade propeller. Mod. III changes the gear ratio further and uses a 6 blade propeller to reduce noise. The performance and weight penalties may or my not be acceptable. As in other configurations, adding blades and changing gear ratios probably affects cost.

Based on the above study it appears that some noise reduction is possible without significantly affecting weight or performance. This is based on analysis so would have to be proved experimentally. The cost of the changes may or may not be acceptable. If geared engines are used, their cost and reliability must be considered.

Rathgeber and Sipes, 1977 - In this report[2.14] the effects of various parameters on 305 m (1000 ft) flyover noise is documented. The effect of helical tip Mach number (MH) on A-Weighted noise is shown in Figure 2.17. The increasing effect of MH on A-Weighted as MH increases can be seen. The effect of engine exhaust configuration can also be seen in Figure 2.17 Data presented show that turbocharged engines are lower in noise than naturally aspirated engines. Although details are not presented, it appears that the turbocharged 3 blade installations can be 1 to 5 dBA lower than naturally aspirated 3 blade installations at tip helical Mach number (MH) between 0.83 and 0.87.

Tip thickness effects are also documented. Figure 2.18 shows the A-Weighted noise as a function of MH for three different tip thicknesses. There is the suggestion in this figure that the effect of tip thickness on noise increases with increasing MH.

The authors indicate that climb performance is degraded as number of blades increases. Cruise performance is less affected.

The use of reduction drives to reduce MH is discussed. In one case a two stage reduction drive on a rotary-combustion was used. The resulting noise levels were very low, however, because of the added weight, the aircraft had zero payload. A system with a single reduction drive was tried but did not appear to provide a worthwhile benefit for the added weight.

Shrouded propellers as a means to reduce noise are discussed briefly. No significant benefits were found for the configurations tested.

Muhlbauer, 1978 - In this report[2.15] some general comments on noise reduction are provided in the context of the author's experience with propellers made of wood composite (wood blades covered with fiberglass with metal tips). Various noise reductions were measured when the existing fixed pitch propellers were replaced by variable pitch propellers with wood composite blades. However, the test conditions are not included so exact noise reduction values are not relevant. The existing propellers have 3 blades and are slightly smaller in diameter. The weight of the 3 blade propeller can be equal to or less than the weight of a current 2 blade metal propeller. The cost of the 3 blade propeller is approximately two times that of the 2 blade metal propeller.

Regarding engine exhaust noise, Muhlbauer states that "the exhaust (muffler) system of general aviation aircraft is far behind the state-of-the art in cars. Considering weight and dimensional limitations, real research and development is needed to bring the engine noise down to the present car values.":

Masefield, 1978 - A review of the work done in Germany and Switzerland to reduce light aircraft noise is described in this paper[2.16]. Only the A-Weighted overall noise is reported along with general parameters of the blade geometry. Noise is found to increase with tip Mach number. The slope of noise with tip Mach number is noted to be different for different propellers but the reasons for this are not presented. The following closing comment of this paper is of interest as it may still, to a great extent, be true 17 years after it was written:

> "For the long term therefore it should be investigated to manufacture a completely new generation of propellers possibly using the supercritical profile techniques. The governmental pressure is apparent in Europe, but by far the greatest manufacturers of propellers are in the United States and as yet there are no products on the market with advanced designs for low noise."

Davis, 1979 - In this paper[2.17], the impact of using airfoils with performance better than that of NACA Series 16 or 65 airfoils is described. With this new airfoil section the propeller blade loading can be increased so performance can be maintained without a weight penalty at a lower RPM, thus reducing noise. These new propellers were designed for use on turbine engines. The baseline propeller had the following characteristics: takeoff power, 650 hp; propeller diameter, 90 inches; propeller speed, 2200 RPM; and blade number, 3. it is claimed that the use of the new airfoil sections allows the propeller to be run at a reduced RPM of 2000 with a resultant reduction of 3 dB (note that the text does not indicate whether this is weighted or unweighted). The weight of the new propeller is stated to be 85.6% of the original design using older airfoil designs.

The same type of study was done for a typical piston engine installation. Here the baseline propeller had 2 blades, a diameter of 80 inches, an RPM of 2700 and engine power of 300. A study is reported that indicates that cruise efficiency can be maintained while reducing diameter to 74 inches. This is claimed to reduce noise to 80.6 dBA from the 85 dBA level of the baseline propeller.

It should be noted that the above information is based on analytical studies, not experiments. However, the idea of improving propeller performance by improving the airfoil performance may be feasible. This would then allow a reduction in propeller diameter with an associated reduction in noise. Also, it should be noted that the advanced airfoils of the type discussed in this report are now in common use on larger commuter airplanes. These may also be in use on recent propeller designs, particularly those in Europe.

Klatte and Metzger, 1979 - 1981 - These reports[2.18-2.19] describe an extensive study of the influence of noise reduction and weight and cost of propellers used in the General Aviation aircraft. Only propeller modifications were considered. Engine modifications such as the addition of a gearbox to reduce RPM were not considered. This study is unique in that it attempts to deal with the practical aspects of propeller design where noise, performance, weight and cost are all considered.

Prediction methods were needed in the study for noise, performance, weight, cost and required thrust. Noise predictions were done with a frequency domain method based on work by Hanson. This method was originally developed for Prop-Fan noise prediction. It includes methods for predicting tone and broadband noise components. Noise due to loading, thickness and quadruple (non-linear) sources are predicted. The effect of the blade sweep can be assessed with the method.

Performance was predicted by a proven method used to design many propellers in common use. The method uses two dimensional empirical airfoil data to compute lift and drag distribution on a series of blade elements along the blade radius.

Weight was predicted based on a generalization of the catalog of 1970 manufacturer's weights for solid metal propellers. Evaluation of this method showed that existing propeller weights were calculated with no more than a ±12% error.

Cost was predicted based on a generalization of the catalog of 1978 manufacturer's prices for solid metal propellers.

Reducing the propeller diameter is one common method for reducing propeller noise. However, as the propeller diameter is reduced the slipstream velocity increases so the aircraft drag increases. Therefore, propeller thrust must be increased to maintain a fixed level of airplane performance. The study used a method to predict the required increase in thrust to provide a realistic assessment of the noise reduction that could be achieved with reduced diameter propellers.

Engine noise for the piston engines used was predicted using an empirical generalization. The noise reductions achieved with various propeller configurations is reported with and without the engine noise contribution.

Three airplanes were used in the study, the Beechcraft 35-B33 Deboniar (a single engine example), the Beechcraft 76 Duchess (a light twin engine example) and the deHavilland DHC6 Twin Otter (a heavy twin turbine engine example).

The initial studies concentrated on the approaches to reduce the noise of the single engine Debonair. Initial calculations showed that the existing Debonair propeller noise was dominated by noise due to thickness. Therefore the effect on noise of changes in tip shape were explored. Figure 2.19 shows the planforms of the blade that were evaluated. It was found that the lowest noise was produced by the elliptical tip blade.

Next the effect on noise of unloading the tip was evaluated by changing the twist distribution of the blade. This showed some further reduction.

Next the influence on noise of changing from RAF-6 airfoils to NACA Series 16 airfoils was evaluated. It was found that the performance of the existing propeller with RAF-6 airfoils was lower than a propeller with NACA Series 16 airfoils of equal diameter. Therefore, some reduction in diameter was possible with a resulting reduction in noise. The amount of reduction was predicated on equalling the performance of the existing propeller at both takeoff and 1000 ft flyover. It was found that the existing 7 ft diameter propeller could be reduced by 0.5 ft while still retaining the required performance.

Tip sweep as shown in Figure 2.20 was also considered. The figure shows a rather extreme tip sweep of 52° which is predicted to reduce flyover noise by 5.5 dBA. It was concluded that the reduction achieved by sweep could probably be obtained with less cost

and weight impact by alternate noise reduction methods. Also the structural implications of such sweep were not assessed.

The results of the Debonair study are summarized in Figure 2.21. The configurations are arranged in decreasing noise level from left to right. Two noise levels are presented, (1) the noise of the propeller alone (the lower bars of the upper bar graph), and (2) the noise of the propeller plus engine (the upper bar of the upper bar graph). It was found that configuration 15 of Figure 2.21 showed the greatest noise reduction without a weight or cost penalty. This propeller is a 2 blade thin elliptical tip configuration with a smaller diameter than the exiting propeller. Further reduction can be obtained using a 3 blade propeller with an even smaller diameter and thin elliptical tips. While there is no weight penalty, there is a 24% cost penalty for this configuration. Also a 3 blade propeller with a high degree of tip sweep produced less noise but these require further structural study. It appears that 4 blade propellers were not acceptable because they could not achieve the performance of the existing 2 blade propeller.

The results of the Beech 76 Duchess study are shown in Figure 2.22. Again the configurations are arranged in decreasing noise level from left to right and both propeller alone and propeller plus engine noise are shown. Note that the Duchess propeller planform already incorporates most of the elliptical shape found to be desirable in the Debonair study. Also, it should be noted that the Clark Y airfoils of the existing propeller were predicted to perform worse than the NACA Series 16 airfoils of the study propellers. Therefore, the diameter of the study propellers could be reduced with attendant noise reductions.

Configuration 5, with 2 thin elliptical tip blades shows the best noise reduction without a cost or weight penalty. Further reduction can be obtained without a weight penalty with configuration 7, with 3 thin nominal tip shape blades of smaller diameter but there is a 22% cost penalty. The lowest noise predicted was obtained for a 4 blade propeller with thin elliptical tips. The weight penalty for this propeller was 11%. The cost penalty for this propeller was 57%. Note that exhaust muffling is required to take advantage of the reduction in propeller noise to achieve a reduction in overall airplane noise.

The results of the deHavilland Twin Otter study are shown in Figure 2.23. The engine noise used in the study was based on unpublished analysis of Twin Otter flyover noise. It can be seen that noise can be reduced by using thin elliptical tip blades in 3, 4, and 5 blade configurations. There is no cost or weight penalty predicted for the 3 and 4 blade replacement propellers. The 5 bade configuration shows no weight penalty but a 26 percent cost penalty. One of the 3 blade propellers evaluated was based on a propeller designed for the OV-10 nor the American Rockwell (see Figure 2.24). It has a narrow tip and wide inboard section and has the spanwise load moved inboard.

It was concluded in this report that the most productive approaches to reduce noise are:

1. use of elliptical tip blade planforms;

2. use of the smaller tip airfoil thickness consistent with structural integrity and manufacturing technology.

3. optimization of propeller performance to reduce propeller diameter to a minimum; and

4. use of the largest number of blades consistent with performance, weight, and cost requirements.

Wilby and Galloway, 1979 - This report[2.20] reviews the cost/benefit tradeoffs for applying noise technology to airplanes. One of the airplane types considered is the General Aviation twin piston engine powered class. Three noise reduction concepts are recommended to reduce the noise of the propeller driven aircraft: (1) increase the number of blades on the propeller and reduce its diameter; (2) reduce propeller RPM, and (3) improve the noise reduction performance of exhaust mufflers.

The baseline propeller for this study had 3 blades. The reduced noise propellers were either a 4 blade with 7.7% smaller diameter or 5 blade with 11.5% smaller diameter. The weight impact was estimated to be 20 lb per additional blade. An additional reduction of 3 dB was considered possible with redesigned blade tip shape and blade airfoils.

It was the authors' opinion that an exhaust muffler could be designed to reduce engine noise by 10 dB without performance penalties. The weight impact was estimated to be 5 lb per propeller.

The beneficial effect of using a geared engine to reduce RPM was not considered clear as a noise reduction technique at the time of this report. The authors considered that the addition of external gearboxes to existing engines in order to achieve lower propeller speeds was not reasonable due to the additional weight (50 to 100 lbs per engine) and the complexity of the installation. On the other hand, they considered that a new geared drive engine might be built with no change in weight relative to existing direct drive engines.

Borchers, 1980 - This document is a series of figures used in a specialist meeting on propeller noise[2.21]. Of must interest is the flyover noise levels of airplanes equipped with different propellers. These propellers are shown in Figure 2.25. The measured noise levels in dBA for level flyovers at 305 m altitude at 2700 RPM (and presumably maximum power) are shown in Figure 2.26. The measurements were obtained using a microphone mounted 1.2 m above the ground.

The figure shows the two more standard propellers, the Hoffmann H027 made of wood composite and the Sensenich SE76 made of duraluminum produced the highest noise and flew at the highest speed. The Hoffman HOB27 152 BiBlade showed a reduction in noise relative to the more standard propellers with some loss in airplane speed. The other Hoffmann BiBlade, the HOB27 137, showed further noise reduction accompanied by a more significant loss in airplane speed. The two wide blade propellers, the HO165's, were similar in noise level to the HOB27 137 BiBlade and also similar in flight speed attained. The

HO165BG four blade propeller produced the lowest noise with some loss in maximum flight speed relative to the more standard propellers and the HOB27 BiBlade.

From the above discussion it appears that there is some performance benefit to the BiBlade relative to a wide blade propeller but there is also a noise penalty. The four blade propeller shows a small performance penalty but a large noise benefit relative to more standard 2 blade propellers or the HOB27 BiBlade propeller.

Korkan et al. 1980 - An extensive acoustic sensitivity study is reported in this paper[2.22] which uses analytical methods to explore the effect of various geometric variables when applied to four different candidate airplanes. The four airplanes were (1) the Cessna 172N, a small single piston engine driven high wing airplane, (2) the Cessna 210M, a mid size single piston engine driven high wing airplane, (3) the Cessna 441, twin turbine engine driven low wing executive transport, and (4) the STAT, a hypothetical twin turbine engine driven low wing 19 passenger commuter transport.

The study was conducted by holding all variables constant except the one of interest. The effect, on 1000 ft A-Weighted flyover noise, of varying the variable of interest was calculated.

Figure 2.27 shows the effect on noise of varying the number of blades. It can be seen that the reductions in noise for increasing the number of blades is fairly small; about 2 dB for a change from two to four blades in the C172N and less than 1 dB for increasing the number of blades from three to four for the other airplanes.

The effect on noise of reducing RPM is shown in Figure 2.28. The reduction in noise is fairly significant in all cases but the engine in each case must be modified to produce the full horsepower at reduced RPM. Furthermore there is an efficiency penalty with reduced RPM that may be difficult to recover by propeller redesign.

The effect on noise of reducing blade thickness is shown in Figure 2.29. Some worthwhile reductions can be seen. However, it may not be structurally acceptable to reduce the thickness past some minimum.

The effect on noise of reducing activity factor (a function of blade width), shown in Figure 2.30, is detrimental for all but the Cessna 441. Again there may be structural limits to reduction in activity factor. There may be efficiency changes with activity factor that are unacceptable. In general activity factor is one of the parameters that is optimized to achieve the best compromise between cruise and takeoff performance.

The effect on noise of adding proplets (like winglets on a wing tip) is shown in Figure 2.31. The basic assumption is that this device allows the propeller tip to carry a finite load instead of going to zero as in a conventional propeller. The reductions in noise shown are fairly significant. It is greatest in propellers with lightly loaded tips like those on the Cessna 172N and least on the heavily tip loaded Cessna 441. The authors note that these results must be further evaluated. Since the time of this study, few applications of proplets are known to exist. It is not known whether the noise benefits are less than expected or there are structural reasons for this concept not receiving wider application.

The effect of airfoil improvement was not assessed quantitatively. instead the effect of thickness distribution at zero angle of attack, the thickness distribution at the actual angle of attack and the camber line effect was evaluated separately. The camber line was found to be most significant, i.e. how the airfoil section is pressure loaded. Finding airfoil shapes with higher performance and low noise would require and extensive optimization study which, the authors say, was being examined at the time of the report.

The effect of sweep at the blade tip was studied and found to be beneficial where the tip loading is high as in the Cessna 441 propeller. The other propellers, where tip loading is low, show little effect or can possibly show an increase in the overall level.

Figure 2.32 shows the effect of moving the spanwise peak loading inboard. In the case of the lightly loaded 172N some benefit can be seen. For the 210M and STAT the loading peak must be brought inboard of 80% radius before noise is reduced. The heavily tip loaded 441 (not shown) was found to increase in noise as the peak loading was moved inboard.

The effect on noise of diameter reduction is shown in Figure 2.33. It can be seen that diameter reduction is beneficial except in heavily tip loaded propellers like those on the 441.

In their summary the authors state that "from an acoustic point of view, variation of a propeller parameter may result in a reduction in noise for one aircraft/propeller combination and an increase in noise for another aircraft/propeller combination, the result of which is dependent on the predominant noise source." The approach used in this study can be used to identify the component with the largest noise reduction without an efficiency loss. This can then be the starting point for further design refinement.

Sullivan et al. 1981 - This paper[2.23] presents a summary of theoretical studies of General Aviation propeller with proplets on the blade tips and propellers consisting of two blades oriented in parallel like the wings of a biplane (biblades). In general these configurations showed some potential for improving efficiency (1 to 5%) but noise was in general higher. The authors suggest that there may be a combination of a reduced diameter propeller with a tip device that maintains aerodynamic efficiency while obtaining a noise reduction because of the reduced tip Mach number.

Succi, 1981 - In this paper[2.24] the experimental flight test results of an extensive analytical and model experimental program are shown. The basic concept demonstrated is to move the peak propeller loading inboard on the blade and increase the chord on the inboard sections of the blade to minimize performance losses.

The propeller was designed for the Cessna 172, a 150 hp single engine airplane. The performance and noise of the airplane with the experimental propeller was compared with that having a production propeller. The experimental propeller was designed to match the power absorption of the production propeller at the design flyover condition. Since off design calculations indicated hat the initial design configuration would absorb too much power at low speeds the radius was reduced to 92.5% of that of the production propeller. Another factor considered was the danger of overspeeding the engine. To avoid this problem the experimental propeller was designed to turn 100 RPM slower than the production propeller at full throttle. The limited performance information in the reference showed that the rate of climb was slightly lower for the experimental propeller relative to the production propeller over most of the flight speed range. This is shown in Figure 2.34. The average measured noise reduction of the experimental propeller relative to the production propeller was 4.8 dBA at 1000 ft and 4.4 dBA at 500 ft flyover.

Gregorek et al. 1983 - This paper reports the results of flight tests of four different propellers on a single engine airplane. The planforms for the four blade tested are shown in Figure 2.35. It can be seen that the baseline propeller has two blades and an elliptical tip planform. It is 74 inches in diameter. The OSU 2 blade and 4 blade propeller were both 68 inches diameter and used high lift airfoil sections designed specifically for these propellers. The MIT 3 blade propeller was 69 inches in diameter and used NACA 64000 Series airfoils.

The section thickness/chord and blade angle as a function of radial location is shown in Figure 2.36 for the propellers tested.

Noise data was obtained by using a microphone mounted on a boom attached to the landing gear of the test aircraft. The distance from the microphone to the propeller centerline was 6.3 ft.

The noise data shown in Figure 2.37 indicate that the increase in number of blades reduces noise The performance information was more difficult to interpret as the blade pitch was fixed. The authors state that:

"All propellers tested showed acceptable performance in takeoff, climb, and maximum speed. The MIT-designed three-blade propeller was optimized for high-speed flight, and showed slightly better climb and maximum-speed performance than the other propellers, at the expense of takeoff acceleration. The OSU-designed propellers were optimized for lower speeds; they showed the best takeoff performance of any of the experimental propellers, with slightly reduced climb and cruise performance as compared to the MIT three-blade propeller. All of the experimental propellers were slightly better than the baseline propeller in climb performance, and slightly degraded in takeoff and maximum speed. It may be seen that reductions in propeller noise at a fixed RPM were achieved."

Salikuddin et al. 1984 - In this report[2.26] the possibility of reducing propeller noise by adding an active secondary noise source is explored. This work was prompted by an interest in reducing cabin noise of advanced high speed turboprops (Prop-Fans). It is possible that these concepts could also be used to reduce far field noise below the airplane but would probably not reduce noise in all directions.

Initial tests used simulated propeller primary and secondary sources. Noise reduction of a sinusoidal signal showed a reduction of 8 to 14 dB on a surface (fuselage) in the frequency range form 200 to 1000 Hz. Tests conducted with a recording of the noise from a 1/10 scale model propeller showed an average noise reduction of 15 dB at the first two harmonics and a 5 dB at the third and fourth harmonics of blade passage frequency. When the active noise control concept was applied to an actual 1/10 scale model propeller operated in an anechoic wind tunnel the reduction in noise on the fuselage has 8 dB at the blade passage frequency and 2 dB at the second harmonic. The lower performance is attributed by the authors to (a) the contamination of the primary source measurement by the secondary noise and (b) distortion of the secondary signal due to the non-flat amplitude and the non-linear phase responses of the acoustic driver and associated duct work (of the secondary source)." This duct work can be seen in the test setup of Figure 2.38. It is the tube with the curved end which leads from the secondary source to a location near the propeller.

Dobrzynski, 1986 - This paper[2.27] is an evaluation of the tests done in the German Dutch DNW tunnel on square tip and round tip 2 blade General Aviation propellers operated at varying tip speeds, powers and angle of attack. Figure 2.39 summarizes the major findings in this test program. Figure 2.39 is a plot of maximum A-Weighted sound pressure level which has been normalized to a 4 meter distance between the axis of propeller rotation and the measuring microphones and approximately adjusted to a constant power coefficient.

The A-Weighted levels are plotted versus the helical bade tip Mach number (the combination of flight Mach number and flight speed) as corrected for the effect of the angle of attack on the blade approaching the microphone. This correction increases the Helical blade tip Mach number at simulated climb angle of attack. The effect of tip shape shown in Figure 2.39 is approximately 5.5 dBA at 2700 RPM (the cluster of data between 0.83 and

09 helical blade tip Mach number), 4 dBA at 2400 RPM (the cluster of data between 0.73 and 0.8 helical blade-tip Mach number), 3 dBA at 2100 RPM (the cluster of data between 0.65 and 0.69 helical blade-tip Mach number), and 2 dBA at 1800 RPM (the cluster of data between 0.56 and 0.60 helical blade-tip Mach number).

The effect of downtilt of the propeller axis was also documented for the propellers tested. It varied from approximately 0.7 dBA per degree of downtilt at 2700 RPM to approximately 0.4 dBA per degree of downtilt at 1800 RPM.

Jones, 1986 - This report[2.28] summarizes a set of flyover noise measurements on the Piper Cherokee Lance (PA-32R-300), a single engine monoplane with retractable landing gear. The engine was a 300 hp Lycoming IO-540-KIG5 Flat 6 cylinder normally aspirated engine. It was equipped with a Hartzell 2 blade metal constant speed propeller 80 inches in diameter. This is the same round tip propeller earlier tested under isolated conditions in the DNW wind tunnel.

The information of interest is (1) the engine noise contribution to the total aircraft noise; (2) the reduction in noise with reduction in tip speed (RPM); and (3) the effect on noise of inflow angle to the propeller.

Table 2.14 summarizes the pertinent information. Note that both takeoff (TO) and level flyover (LFO) data was obtained. The RPM ranged from 2140 to 2780. At 2780 RPM it is expected that transonic nonlinear noise (quadrupole) may be present. Data was also obtained at intermediate RPM's between 2440 and 2640 which could be considered for noise reduction in a derated engine. Noise data is shown for a ground microphone and a microphone 4 ft above the ground (as used in certification).

The engine noise contribution to the total maximum A-Weighted level of the aircraft which is shown in the table was obtained by analyzing narrow band noise spectra such as that shown in the lower graph of Figure 2.40. The upper graph identifies the tones that are produced by the engine (Labeled E) the propeller (labeled P) and a combination of propeller and engine (labeled C). The same data with A-Weighting is shown in the lower graph. Engine noise components can be extracted in the same way as they were in the upper graph.

Figure 2.41 shows how the engine noise becomes a more significant part of the maximum A-Weighed noise spectrum as the RPM of the propeller (engine) is reduced. The bottom graph of Figure 2.41 shows the high RPM (2780) case with the propeller generated tones at harmonics of 92.7 Hz at high levels over 70 dB extending from low frequencies to 1200 Hz. The engine tones at harmonics of 139 Hz are at lower levels beginning at 70 dB and dropping to approximately 50 dB at 1200 Hz.

At the lowest RPM case (2460) shown at the top of Figure 2.41 the engine noise components at harmonics of 123 Hz have a similar character to those of the high RPM (2780) case in the bottom graph but the propeller tones at harmonics of 82 Hz drop rapidly with increasing frequency. The graph in the center of figure 2.41 shows an intermediate case at 2630 RPM.

The result of the above evaluation is shown in Figure 2.42. The left figure shows the maximum A-Weighted level for the data obtained with a microphone mounted 4 ft above the ground. The right figure shows the data obtained with a microphone mounted very close to the ground. Data is shown for 75% and 55% power. The upper curves in each case show the level of engine plus propeller. The lower curves in each case show the level of the propeller alone.

For the 75% power cases, the engine contribution is not significant for the highest RPM (highest helical tip Mach number) cases F and K. When the RPM is reduced to 2440 at case M it can be seen that engine noise makes a difference of almost 1 dB. Reducing the RPM to 2240 at condition O shows the engine to make a difference of about 2 dB.

The 55% power cases show similar results. however the RPM's are lower (condition I at 2570 RPM, condition P at 2320 RPM and condition Q at 2140 RPM). The sacrifice in performance at conditions P and Q would probably be unacceptable.

From the above discussion it appears that engine noise suppression may be useful in installations with 2 blade propellers operating at 2400 RPM or less. If propellers are modified to reduce noise, engine noise suppression may be required even at higher RPM.

Figure 2.43 shows the effect of changing the inflow angle to the propeller axis of rotation. A negative angle in this figure indicates that the axis is rotated down in the forward direction. As in Figure 2.42, the left graph sows data obtained with a microphone mounted 4 ft above the ground while the right graph shows data obtained with a microphone mounted close to the ground. The line formed using conditions A, B, C, and D for 96% power and 2780 RPM show a reduction of about 3 dB for a downtilt of 4° from 0°. The line formed using conditions E, F, G, and H for 77% power and 2780 RPM show a reduction of about 2 dB for a downtilt of 4° from 0°. At the line formed by conditions K and L for 77% power and 2630 RPM similar reductions are seen. However at the 55% power 2570 RPM conditions (I and J) and 2450 RPM conditions (M and N) the reductions are less. It appears from this data that downtilt is more beneficial at the higher RPM and power conditions.

<u>Raisbeck and Mills, 1987</u> - This paper[2.29] reports the effects of replacing the standard 3 blade propellers on the Beech Super King Air 200 and the deHavilland DHC6-300 Twin Otter with 4 blade propellers. The characteristics of the standard and replacement propellers are shown in Table 2.15. It can be seen that the diameter of the replacement propellers is less than the standard propellers. In the case of the Beech Super King Air 200 a weight penalty of 11 pounds is seen for the installation of the replacement propeller. The flyover certification noise is reduced by 4.2 dBA for the Beech Super King Air 200 and by 5.1 dBA for the deHavilland DHC6-300 Twin Otter.

Also it is of interest to note that the replacement propellers reduce the large blockage effects of round blade shanks on inlet flow to the engine. On the Super King Air with the replacement propeller, the twin engine rate of climb is increased by 480 ft/min, the initial cruise altitude is increased by 2000 ft and block fuel consumption is reduced by approximately 9%. On the Twin Otter the increased ram air recovery of the replacement propeller installation boosted engine output horsepower by 5% and increased its flat rating by 9° F for 1400 ft in altitude. Therefore the noise reduction achieved by the replacement propellers in this case was accompanied by an increase in airplane performance. There was a small weight penalty. The cost penalty is not known. Also, it is not known whether there was any change in durability for the replacement propeller installation.

Dobrzynski, 1990 -1993 - In these reports[2.30-2.32] the concept of unsymmetrical blade spacing of a propeller with four or more blades is discussed. Only even blade number configurations are considered in order to avoid balancing problems. The typical propeller geometry considered is shown in Figure 2.44 for a 6 blade propeller made by stacking 2 blade propellers with a spacing of x and with the angle between them of ϵ.

Analytical predictions of the noise reduction potential of a 6 blade propeller 3 meters in diameter operating at a 0.7 tip helical Mach number (MH) are shown in Figure 2.45. It can be seen that the maximum reduction in A-Weighted noise is achieved at an ϵ of 20°. Dobrzynski states that other calculations for 4 and 6 blade propellers were run to determine the maximum reduction in A-Weighted noise. These are summarized in Figure 2.46. The best 6 blade configuration achieves a reduction of 4.3 dB at a 0.65 MH. The best 4 blade configuration achieves a reduction of 4.3 dB at a 0.52 MH. These reductions were calculated for a propeller diameter of 3 meters (9.843 ft). Figure 2.47 shows how diameter affects the calculated reductions at 0.7 MH. for the 6 blade configuration the reduction calculated increases with increasing diameter. it appears that the larger commuter aircraft, where diameters exceed the reference 3 meter diameter, would benefit the most from the unsymmetrical propeller geometry. The 4 blade configuration does not show as much noise reduction dependence on diameter in Figure 2.47 but the reference MH of 0.7 is higher than optimum for the four blade configuration (see Figure 2.46). Tests were run an a 1.7 meter diameter 6 blade configuration in the DNW wind tunnel. Results generally confirm the analytical work discussed above. No detrimental effect on propeller performance was observed at the test conditions.

Kallergis, 1990-1993 - In these papers[2.33-2.35] the reduction of flyover noise from piston engine propeller driven General Aviation airplanes by superposition of the propeller and exhaust noise is discussed. Tests were conducted on a Cessna 207A with a 3 blade propeller and a 6 cylinder 4 stroke engine. The phase relationship of the propeller and exhaust noise was adjusted using a plate between the engine shaft and propeller that could by physically rotated in small angular increments. In order to obtain the maximum noise reduction by phase cancellation the engine exhaust port and the downgoing blade must be less than a half wavelength distance apart for the lowest frequency of interest. Also the exhaust pipes from the 6 cylinders of the engine must be collected into one exhaust port to obtain equal timing and noise level for each firing pulse. The measured reductions in flyover noise were 1 dBA for a microphone mounted flush with the ground and 2 dBA for a microphone mounted 1.2 m above the ground. It is possible that larger noise reductions may be achieved with further optimization of the configuration. In particular, if the propeller noise is reduced to same level as the engine exhaust, then greater reductions should be possible.

Weiblen, 1992 - This report[2.36] reviews the experience of one propeller manufacturer in Germany in reducing noise of propeller driven airplanes. The approach often used is to replace the existing fixed pitch propeller with a variable pitch propeller with more blades. The new propellers have high performance airfoils on the outer portion of the blades and Clark Y airfoils on the thicker inner portions of the blades. The replacement propellers are built from wood with a fibreglass covering..

It is noted in this report than the pressure distribution along the blade radius normally has its maximum at 70 to 80 percent of the blade radius. The modified designs have an altered blade planform, angle of attack and airfoils that produce the highest lift between 50 to 80 percent of the blade radius.

Based on test experience, Weiblen concludes that the following noise reduction benefits are possible:

a. 2 -3 dB/100 RPM for propeller speed reduction;

b. 2 dB/ 10 cm for propeller diameter reduction;

c. 2 dB/blade for increased blade number and reduced diameter. Noise is not reduced unless diameter is reduced;

d. Noise is reduced for a change from fixed to variable pitch in conjunction with changes listed above.

Dobrzynski and Gehlhar, 1993 - In this paper[2.37] the effect on certification noise of increasing the number of blades of a propeller is documented. The characteristics of the blades used in the program are shown in Table 2.16. The diameter is reduced by about 5% per additional blade based on experience of the propeller manufacturer. The blades used were not uniform in profile and contour since the propellers were made form available blade configurations. Note that the increase in propeller mass (weight) does not increase dramatically as number of blades increases. The worst case is the 6 blade propeller with a mass 35% greater than the 2 blade propeller. In fact, the 4 blade propeller is 8% lighter than the 2 blade propeller.

The level flyover noise for the different propellers at a height of 300 meters is shown in Figure 2.48. This data is obtained at a constant RPM of 2700 so the reduction in diameter with increase in number of blades reduces the tip helical Mach number. Figure 2.48 shows that increasing the number of blades reduces noise. The linear(unweighted) level and A-

Weighted levels show fairly significant reductions for the 3 and 4 blade configurations. The lack of further reductions for the 5 and 6 blade configurations is attributed to engine noise.

The effect on A-Weighed climb out noise of increasing the number of blades is shown in Figure 2.49. Here the noise is seen to be reduced as the number of blades increases from 2 to 4 with no further reduction for 6 blades. The 5 blade data is considered suspect. Dobrzynski suggests that an interaction of the engine exhaust with the 5 blade data cause the A-Weighted levels to be abnormally high. Also it can be seen in Figure 2.49 that reducing engine RPM reduces noise by an additional amount.

In conclusion, Dobrzynski states that test "results show a continuous degradation in aircraft climb performance, up to 20% for a 6 blade propeller, when compared with the 2 blade reference propeller. At the same time the A-Weighted flyover noise levels decrease by 9 dBA. However, the 4 blade propeller already achieves a noise reduction of almost 8 dB, again compared with the reference propeller's noise radiation." He recommends the 4 blade propeller for retrofitting current aircraft.

Lohmann, 1993 - This report[2.38] reviews the use of a computer code that acoustically optimizes the configuration of a propeller consisting of blades with different and asymmetrical sweep in the blade planform, i.e. each blade making up the propeller has a different sweep. This concept extends that which was used in the development of the swept blade planforms of the Prop-Fan advanced high speed turboprop. In the Prop-Fan all blades making up a propeller were identical and had the same sweep. This caused the noise to be reduced by interference of noise produced at different spanwise locations on the blades. In the configurations studied by Lohmann the sweep of each blade making up a propeller is allowed to have a different sweep. Therefore noise reduction occurs by interference between the different blades making up a propeller. In Lohmann's configurations the usual harmonics occur plus a dense field of subharmonics.

Lohmann's report is theoretical in nature. It reviews the noise reduction potential of the asymmetrical sweep concept without regard to difficulties in structural design and aerodynamics. The approximate overall noise reduction potential calculated for various blade numbers is 5 dB for 2 blades, 6 dB for 4 blades and 11 dB for 6 blades. To achieve these reductions the sweep angles at the tip are as high as 45°, a value not likely to be acceptable from a structural design standpoint.

Figure 2.50 shows the calculated noise reductions for the first three harmonics of 4 blade propellers. The configurations in the left chart use different sweep angles for each blade making up the propeller. A sketch of the tip sweep is shown at the top of the figure. The configurations in the right chart use the same sweep angle for each bade as in Prop-Fan configurations. Lohmann points out that the reduction in the third harmonic for the unsymmetrical configuration on the left is particularly beneficial for reducing A-Weighted level.

Chusseau, et. al. 1993 - This paper[2.39] reports an acoustic and aerodynamic parametric study of light propeller airplane noise. The study makes use of frequency domain method where the monopole (thickness) and dipole (loading) sources are included. The aerodynamic propeller performance needed for an acoustic and aerodynamic study is predicted with a curved lifting line method.

It is well known that there is an optimum size blade for a given performance requirement and number of blades. The authors evaluate this for 2, 3, 4, and 5 blades for the reference airplane which has an engine operating at 2700 RPM at a power of 147.2 kw. The reference propeller is 1.88 m in diameter with 2 blades The airplane is assumed to operate in level flight at 300 meters altitude.

In scaling the blade diameter, the thickness and chord change, and the relative maximum thickness remains the same. For maximum thrust, the blade scale is reduced as number of blades increases. Also as number of blades increases the maximum achievable thrust becomes less although on a percentage of reference thrust (2000 Newtons) the loss is fairly small (0.75% for 3 blades, 1.5% for 4 blades, and 2.75% for 5 blades).

For a given blade number the study results showed that noise is less as blade size becomes less. As blade number increases there is a further reduction in noise. The reductions expected are as follows:

two to three blades	100 to 90 scale factor	~4 dB reduction
three to four blades	90 to 85 scale factor	~4.5 dB reduction
four to five blades	85 to 80 scale factor	~4.5 dB reduction

Cox, 1995 - In this article[2.40] the Rushmeyer R90 low wing, piston engine driven, 4 seat, General Aviation airplane is discussed. This airplane is of interest because it is a new design (certified in Europe under JAR 23 amendment 34 in 1990) and because it appears to have been designed for low noise.

The propeller is a four blade wood/composite (covered with fiberglass) constant speed propeller 75 inches in diameter. It also has a protective leading edge aluminum strip. The engine is rated at 230 hp at takeoff. It has been derated from 2575 to 2400 for this application. The engine also has a stainless steel muffler.

The noise level under International Civil Aviation Organization 1000 ft flyover certification requirements quoted in this article is 66 dB as compared with a limit of 74 dB.

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3.0 PISTON ENGINE NOISE REDUCTION LITERATURE REVIEW

In this section, some of the extensive literature on mufflers as well as other piston engine exhaust noise reduction methods are discussed. The reader interested in this subject can find many more references in texts such as that of Munjal which is reviewed below.

Active noise control of exhaust noise by electronic control of loudspeakers is not discussed in this literature review. It is known that it is a concept that is being tested on city buses. It is also being explored as an alternate to an automobile muffler. The technical feasibility of this concept has been well proven in other applications. However, there are still questions about the cost, weight, size, and durability of such a system. The passive systems appear to offer a more near term exhaust noise solution.

Air Commerce Bulletin, 1932 - The author of this report[3.1] by the U.S. Department of Commerce Aeronautics Branch is not given. It reviews measurements of noise reduction by ten different mufflers installed on a stationery 180 hp V-8 water cooled Hispano-Suiza aircraft engine which drove a hydraulic dynamometer (to eliminate the noise that would normally be produced by the propeller).

Reference tests were conducted in several ways: (1) with the engine exhaust ports open to the atmosphere, (2) with the exhaust ports manifolded together on each side of the engine; (3) with the manifolds connected together to form a single exhaust pipe; and (4) with the single exhaust pipe passed through a muffler consisting of three barrels buried in the ground to effectively eliminate all exhaust noise.

Several muffler concepts were investigated in this program. The Bureau of Standards configurations consisted of multiple plates separated by washers to form narrow open passages to restrict the expansion of expansion of exhaust gases. Three of these configurations were tested: (1) B.S. 1 which was attached directly to each exhaust port (8 separate mufflers); (2) B.S. 3 which was attached to each bank of exhaust ports (2 separate mufflers); and (3) B.S. 2 which was attached to the single exhaust pipe at the end of the manifolded exhaust pipes.

Two other mufflers were tested which were designed for attachment to the manifold exhaust pipes. The Burgess was a straight through muffler consisting of a perforated pipe 3 inches in diameter and 5 1/2 ft long encased in a cylinder 7 inches in diameter and 5 ft long. The space between the perforated pipe and the cylinder are filled with sound absorbing material (the material is not identified in the report). Two of these mufflers together weighed 110 pounds but it was claimed that the weight could be considerably reduced. This muffler appear to be an early version of the straight through bulk absorber type which has been used recently on some General Aviation airplanes in Europe.

The Corless was the second muffler attached to a manifolded pipe attached to each tank of the engine. It consisted of a rotor with a governor brake where the exhaust gases are directed to cause the rotor to turn. Two of these mufflers were used (one for each side manifold). The weight for two mufflers was about 32 lbs. It appears that this muffler is the early concept of the turbocharger on modern engines, which is known to reduce exhaust noise.

In addition to the B.S. 2 muffler described earlier, four other muffler configurations were tested when attached to the combined single exhaust from the manifolded exhaust pipes. The first of these is the "Sikorsky" which according to the article:

> "consists of a pipe 3 inches in diameter open to the atmosphere at both ends, around which is a shell approximately 9 inches in diameter and 31 1/4 inches long. The space between the pipe and the shell is divided into compartments by baffles punched with holes. The entrance to the muffler is a 90° elbow ,4 1/2 inches in diameter so arranged that the gases enter the space between the 3 inch pipe and the outer shell with a swirling motion. The gas is discharged to the atmosphere through holes in a cone at the end of the muffler and through holes in the 3 inch pipe. The muffler weighed 13.9 pounds."

This muffler appears to be an early version of the resonator muffler currently in use in automobiles but with some unique features.

The second muffler was the "Watson" which consisted of a cartridge of loosely rolled copper-wire mesh about 18 inches long and 2 7/8 inches in diameter. This was inserted in the end of a 24 inch length of 3 inch pipe to form the muffler. This muffler weighed 2 1.2 pounds. In concept this muffler is similar to the B.S. types discussed earlier but would probably produce higher pressure drop since the mesh restricted the exhaust pipe. In modern versions of this muffler , the copper mesh would be replaced by a material such as porous sintered metal and the diameter of the exhaust pipe might be increased to reduce the pressure drop of the exhaust system.

The third muffler was the "Wolford" which consisted of a series of three egg-shaped chambers of gradually increasing diameter in series. Within each egg shaped chamber a hollow egg shaped body of smaller diameter was suspended. This muffler weighted 10 3/4 lbs. It appears to be another tuned system but the role of the bodies suspended in the three egg shaped chambers is not clear.

The fourth and fifth mufflers of different size were the "Rowan." The complex configuration of these mufflers as described in the report is as follows:

> "The outer shell of the large muffler is circular in cross section and tapers from a diameter of 6 inches to a diameter of 5 inches in a length of 36 inches, and then tapers to a diameter of 3 inches in a length of 18 inches. Louvers or slots are provided in the 18-inch section for discharging the gases to the atmosphere. The shell is flared at the large end in order to collect air from

the slip stream for cooling purposes. A rectangular box 4 1/2 x 4 1/2 by 40 inches is inserted in the 36 inch section of the shell. The exhaust gases enter the rectangular box through a cylindrical section on the head end and are discharged into the 18 inch section of the shell where the gases are mixed with the air collected from the slip stream. Inside the box there are a number of deflectors which give a swirling notion to the gases. The (large) muffler weighed 16 pounds. The small muffler is of the same general design but constructed of slightly heavier material. The weight of the small muffler was 15 1/2 pounds."

The acoustic environment for the tests does not appear to be ideal based on the report. Data was obtained at six microphone stations. As an indication of the effects of the mufflers on airplane flyover noise, the data from microphones 80 ft from the engine will be reviewed. This information is shown in Table 3.1. Note that the information is grouped by exhaust port configuration, i.e. open ports, side manifolds, manifolds collected to a single exhaust pipe, and barrels. For the category labelled barrels the exhaust form the single exhaust pipe from the manifolds is passed through the underground barrels so the sound levels listed are effectively the engine clatter that remains.

it can be seen that adding the side manifolds and collecting these to a single exhaust pipe has beneficial effects on the noise level. Considering the open port configurations both the B.S. configurations produce significant reductions in overall noise (15 dB for B.S. 1 and 15 dB for B.S. 3). Most of this reduction occurs at the higher frequencies above 5000 Hz.

Considering the side manifold configurations, the Burgess bulk absorber muffler is not very effective as compared with the Corless spinning rotor configuration which reduces overall noise by 11 dB and reduces noise in the 0 to 250 Hz band by 11 dB. The Corless muffler also appears effective above 500 Hz as well. It was not a reliable configuration however. Difficulty in lubricating the bearings was experienced and one of the rotors failed during test. This could be compared with the early reliability difficulties with turbochargers when they were introduced on automobiles. Today the more widespread use of turbochargers indicates that these earlier reliability problems have been solved.

Considering the configurations with the manifolds collected to a single exhaust pipe. the Watson wire mesh cartridge looks most attractive considering it weighted only 2 1/2 lbs. Again as in the open exhaust port muffler tests, the B.S. configuration can be seen to be effective at frequencies above 1500 Hz. The Rowan data is incomplete as the filter set was not available for the test.

In closing it should be noted that all of the mufflers tested were considered experimental. It is interesting that some of the concepts tested have been used in recent muffler designs.

London, 1940 - In this general report of progress in noise reduction in airplanes[3.2], the author includes a discussion of engine exhaust noise reduction. Apparently both the bulk absorber and tuned cavity mufflers were considered at the time for aircraft engine muffling.

Tests had been conducted by the National Bureau of Standards on various experimental and commercial mufflers. Of the 10 mufflers tested, half reduced the exhaust noise by 5 dB and the other half reduced the exhaust noise by 10 dB. The loss in horsepower due to the mufflers was less than 2%.

In addition to muffler tests, the effects of manifolds and exhaust tubes on engine exhaust noise had been evaluated. . Reductions of 7 to 13 dB were reported for various manifold and exhaust pipe configurations with horsepower losses from 1 to 3%.

Czarnecki and Davis, 1948 - This report[3.3] documents the evaluation of the muffler used in the flight test reported by Vogeley[2.1] where a light reconnaissance airplane with a six cylinder four stroke 185 horsepower engine was modified to reduce flyover noise. The muffler was designed using an early theory. It is a simple straight-through double expansion chamber design as shown in Figure 3.1. No effort to reduce the size of the muffler was made as the objective of the program was to demonstrate the possibility, not feasibility, of quieting engine exhausts with reasonable back pressures.

The muffler installed on the airplane with and without a surrounding heat shield is shown in Figure 3.2. The engine back pressure caused by the muffler was 4.7 inches Hg at an engine RPM of 2790. This compares with a back pressure of 3.5 inches Hg for the unmodified exhaust system. the muffler reduced the noise of the engine by 10 decibels at 2790 RPM and 15 decibels at 1650 RPM. The addition of the long tail pipe with a right angle bend reduced the noise further by 5 decibels at some engine speeds.

Davis and Czarnecki, 1949 - This report summarizes the results of tests of a wide variety of mufflers (68 test configurations) installed on a six cylinder, direct drive, four stroke of 435 cubic-inch displacement rated at 185 hp at 2550 RPM. In general the mufflers that provided significant noise reduction were fairly large so they would be difficult to integrate into a production airplane. It is noted that smaller mufflers could be designed if the operating RPM range was restricted. One attempt to design an expansion chamber muffler to fit within the space available within the engine cavity was unsuccessful as the flat surfaces of the muffler vibrated as a result of engine firing pulses.

One of the most effective mufflers consisted of a singe expansion chamber and a single resonant chamber in combination. It provided excellent attenuation with a reasonable back pressure and was only 30 inches long (considerably shorter than many of the other mufflers tested in this program). Conclusions of interest included:

a. Both resonant-chamber and expansion-chamber mufflers require large chamber volumes to reduce low-frequency noise (the dominant noise is at the lowest firing frequency of the engine).

b. Mufflers of a given cross-sectional area of either circular or oval cross section, with other dimensions the same, appear to give equal (noise reduction) results.

c. The lower the required back pressure, the larger the muffler must be.

d. The straight-through or resonant-chamber mufflers have lower back pressure, in general, than the expansion-chamber mufflers.

e. The tail-pipe configuration (length or bends) may have a large effect on the exhaust system noise characteristics.

Parrott, 1973 - This report[3.5] describes a method for designing expansion chamber mufflers. It is an improvement of transmission-line theory to account for the effect of exhaust gas flow on the properties of the muffler. The computer program for this method includes an optimization procedure that adjusts muffler parameters within specified geometric constraints to achieve a minimum specified transmission loss over a specified frequency range.

A test case is discussed where a muffler was designed to reduce the engine noise of a helicopter. This is the helicopter discussed by Pegg and Hilton in experiments with five different mufflers[3.6]. One of these mufflers was the same as that discussed in this report by Parrott.

Parrott found that the muffler shown in Figure 3.3 which was designed by the computer program reduced the engine exhaust noise by 11 dBA although the desired reduction was 15 to 20 dBA. He found that the noise in the 320 to 520 Hz frequency range increased when the muffler was installed, which he attributed to self noise generated by the muffler system.

Parrott states that the weight of the entire system was 21.3 kg (47 lbs.).

Pegg and Hilton, 1974 - This report[3.6] summarizes the study of noise reduction of a six cylinder horizontally opposed engine at 3200 RPM when mounted on a helicopter. The expansion chamber mufflers tested were designed using a technique for optimizing muffler configuration and minimizing performance penalties[3.5]. An automotive muffler was also tested for comparison. The configurations tested are shown in Figure 3.4. It can be seen that the overall length of the chambers in these mufflers is between 30 and 36 inches. The noise reduction performance of the mufflers derived from figures in the report are shown in Table 3.2. The noise reduction of configurations A and B can be seen to be quite similar. Configuration C provided useful noise reduction but was not as effective as Configurations A or B. Configuration D was an attempt to improve the acoustic and structural characteristics of the muffler and make it more suitable for a flight vehicle. This muffler performed worse than Configuration A, B or C. The reason for this is not presented in the report. Configuration E, the commercial automotive muffler, provided useful noise reductions but was not as effective as Configuration A or B.

The muffler back pressure for Configurations D and E were similar and were less than 12 1/2 cm Hg at maximum power. The standard exhaust system did not produce any appreciable back pressure. The engine manufacturer guarantees rated power at back pressures up to 5 cm Hg. The limited flight tests conducted during the program did not show any noticeable loss in helicopter performance.

Maglieri and Hubbard, 1975 - This paper[3.7] reviews the results from several other papers where propeller and engine noise reduction concepts for General Aviation airplanes were evaluated. Propeller noise is identified as the most important contributor to total aircraft noise. Piston engine exhaust noise is identified as another significant source. Airframe noise is not considered significant.

Figure 3.5 indicates the significance of piston engine noise. The upper plot in Figure 3.5 shows the noise spectrum for a 3 blade turbine powered reconnaissance airplane. This can be compared with the noise spectrum of a 2 blade piston engine powered version of the same airplane in the lower plot of Figure 3.5. It can be seen that the piston engine produces very high levels of tone harmonics while the turbine produces a lower level and more random spectrum with dominant components between 200 and 400 Hz.

Muffling of piston engines is shown to have a significant effect on noise. Figure 3.6 shows the effect of installing a tuned expansion chamber type muffler on a helicopter. It can be seen that the muffler reduces tone noise significantly in the 50 to 250 Hz frequency range and also provides substantial benefits in more broadband type noise in the 600 to 1600 Hz range.

The weight penalty for piston engine exhaust mufflers is summarized in Figure 3.7. The information presented was derived from detectability studies of military airplanes[2.9-2.13]. The noise reductions shown are unweighted. The equivalent A-Weighted noise reductions for these mufflers would be less according to the authors of this paper. It can be seen in this figure that there is a wide range of weight penalties possible as the noise reduction increases. The weight associated with the upper edge of the uncertainty band would undoubtedly be unacceptable. However the weight associated with the lower edge of the band may be reasonable. For example, if 10 dB of noise reduction in a 200 hp (149 kw) engine is desired, the lower edge of the uncertainty and would indicate a muffler weight of about 9 pounds (3.8 kg).

The estimated weight and performance penalty trends for noise reduction in dBA are shown in Figure 3.8 for the 0-1 reconnaissance aircraft. Weight increases as noise is reduced as shown in the left plot of Figure 3.8. It can be seen that a reduction of more than 10 dBA produces very large weight penalties. Since these are estimates, the actual penalties could be larger or smaller. The middle and right plots of Figure 3.8 show the estimated penalties in takeoff distance and cruise speed. If noise reduction less than 16 dBA is desired, there is no takeoff performance penalty. The cruise performance penalty for any noise reduction in the right plot is small.

The authors suggest in their conclusions, that "the required noise reductions for future certification should be possible with potentially small penalties." They do admit however that "there are, at present, no generally accepted engineering methods for development of optimized propellers and exhaust muffler designs from weight and performance penalty standpoints."

Sullivan, 1979 - In two papers[3.3-3.9] the author discusses a method for modeling perforated tube muffler components. The first paper describes the theory and the second describes the applications of the theory. This work is of interest for aircraft engine muffler design as the concentric tube muffler with a central perforated tube is considered desirable for low engine back pressure. Good agreement is shown between measurements and predictions of transmission loss of two mufflers. The first was a simple resonator consisting of a cylindrical cavity surrounding a perforated pipe passing through the resonator. The second was similar to the first except a plug was installed in the perforated tube to force the flow and sound to pass through the perforate and the cavity surrounding the perforated reach the outlet. Of particular interest was the finding that "contrary to popular opinion these devices can be very dissipative, even thought they contain no recognizable dissipative materials(such as bulk absorbers). The controlling mechanism is the high resistivity of the perforation induced by the acoustic/flow environment."

Munjal, 1987 - In this book titled "Acoustics of Ducts and Mufflers: with Application to Exhaust and Ventilation System Design"[3.10], the general subject of the design of mufflers is discussed in depth. This book is an excellent source of references to work done by many researchers over a long period of time. The fundamental concepts and theories for mufflers are discussed in depth but a chapter on the design of mufflers provides more general information on the characteristics of various concepts for muffling piston engines. The following points made in Munjal's book are of particular interest for aircraft engine muffling:

1. Expansion chamber mufflers with inlet and outlet tubes extended within the chamber are better than those with simple expansion chambers;

2. The greater the number of chambers the better the noise reduction;

3. For a given muffler length, the greater the number of chambers the greater the noise reduction at higher frequencies but the lower the noise reduction at lower frequencies;

4. The concentric-tube resonator is a desirable muffler configuration to reduce back pressure on the engine;

5. In practice the total muffler volume is proportional to the total piston displacement of the engine;

6. The A-Weighted noise reduction of a muffler generally increases with the ratio of muffler volume to engine displacement.

Galaitsis and Ver, 1992 - This is a chapter in the book "Noise and Vibration Control Engineering - Principle and Applications" which was edited by Beranek and Ver[3.11]. The chapter of interest is titled "Passive Silencers and Lined Ducts." Both resonator and bulk absorber concepts are reviewed. Of particular interest is the discussion of the effect of basic geometric parameters on the noise reduction of resonator elements. The authors caution that this is only an introduction to a complex subject. They provide a fairly extensive list of references.

Gomolzig, 1995 - In this private communication[3.12] the aircraft engine mufflers manufactured by the Gomolzig company in Germany are shown and the effect of these mufflers on certification noise of various aircraft are summarized. This company has developed a wide variety of mufflers specifically for various General Aviation airplanes. The objective is to retrofit existing airplanes so that they meet the German certification limits which are more stringent than FAA or ICAO limits. Certification levels show that the airplanes with the Gomolzig mufflers meet the German limits and many meet an even more stringent limit 4 dbA lower.

The muffler principles used by Gomolzig include absorption and expansion cavities. Most mufflers appear to be of the straight through type with a central perforated tube surrounded by a concentric cavity filled with absorption material. Most mufflers are mounted outside the fuselage on the bottom of the aircraft because the space needed is not available inside the engine compartment. There are, however, some muffler configurations that do appear to fit within the engine compartment.

The information in this communication indicates that not only do these mufflers reduce the maximum noise of the aircraft flying over but they reduce the noise before and after the maximum even more, thus further reducing the annoyance.

SECTION 3.0 REFERENCES

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4.0 SUMMARY AND CONCLUDING REMARKS

There is a substantial body of literature documenting the experimental and analytical programs that have attempted to show the means to reduce propeller and engine noise of piston engine propeller driven airplanes. Analytical procedures for acoustic and aerodynamic propeller design/tradeoff studies are also available although these are generally complex and require a highly experienced aeroacoustician for their use.

As the noise of the propeller is reduced the piston engine exhaust soon becomes a factor in the flyover noise of the airplane. Experimental and analytical work has been conducted since the early days of aviation to develop effective, low back pressure mufflers. The design procedure for mufflers appears to be in an advanced stage of development.

Based on the above comments, it is surprising that there is a noise problem with current airplanes. In fact, while concepts for reducing propeller and engine exhaust noise do exist they are not widely used because of the cost and weight penalties and the structural limits of existing propeller materials. Reducing propeller RPM, one of the most valuable noise reduction features, requires some type of reduction gear or belt system so that the engine can continue to operate at peak efficiency at high RPM. As an alternative, some airplanes use oversize engines and derate them to operate at lower RPM (which may cause some penalty in weight and fuel consumption).

Another reason for the lack of noise reduction in current aircraft is the lack of new airplane designs in the United States which is the result of reduced sales of new airplanes since 1978.

Finally, there is little incentive to reduce noise as penalties are common in cost weight and reduced performance. If regulations are adopted that force limits on the noise that an airplane can make, then all of industry will comply and all will suffer the penalties equally. This has been called "leveling the playing field".

As evidenced by the list of references, the situation in Europe is somewhat different. There, the public has demanded that airplane noise be reduced so certification limits have been tightened. The airplanes that satisfy FAA and ICAO limits cannot be flown in many European countries without modifications to propellers or engine exhausts. It appears that these European limits may become even more stringent in the future. This scenario has prompted the support of propeller airplane noise reduction research for more than 15 years in the European Economic Community. The result is the manufacture of quiet propellers, mufflers, and, more recently, complete airplanes to satisfy the stringent noise requirements.

The propeller noise reduction concepts found in the literature and discussed in Section 2.0 are listed in Table 4.1. The objective of most work summarized in Table 4.1 was the experimental or analytical demonstration of the noise reduction achievable for General Aviation applications. References 2.9 through 2.13 describe a test series to reduce the detectability of propeller driven airplanes in military reconnaissance missions. It can be seen that most of the references considered reduced RPM, reduced diameter and increased blade number to reduce noise. In some early test programs the reduced RPM and increased number of blades was coupled with increased diameter in an effort to maintain aerodynamic performance while reducing noise. Changes in tip geometry were also popular areas of investigation. Not only rounded or elliptical tip planforms but thinner airfoils near the tip were found to reduce noise. Blade sweep was considered in two analytical studies (references 2.19 - 2.20 and 2.22). Some promise was seen but there is a question of the tradeoff between noise reduction and structure to be settled. Reduced tip load was also found in these two studies and in two test references (2.24 and 2.36) to reduce noise when the propeller was operated in such a manner that the thickness related noise was not dominant.

Muffling of the engine exhaust was included in several test programs (references 2.1 through 2.5 and references 2.9 through 2.13) and opinions were expressed that muffling is needed in a quiet propeller driven airplane (references 2.17 and 2.40).

References 2.18, 2.19, 2.20, 2.25, and 2.36 considered improved aerodynamic efficiency as a means to reduce propeller diameter and/or RPM and increase number of blades while maintaining efficiency and reducing noise. This would be achieved by incorporating new airfoil designs in the propeller. A related concept in Reference 2.22 is the change in the chordwise distribution of airfoil loading to reduce noise.

The BiBlade configuration where paired blades are joined at the tip were considered in References 2.21 and 2.23. Proplets on blade tips were considered in References 2.22 and 2.23.

The reduction in flyover noise caused by downtilting the axis of propeller rotation was considered in a wind tunnel test in Reference 2.27 and in a flight test in Reference 2.28.

The use of asymmetrical blade spacing to reduce flyover noise was investigated in a test program reported in References 2.3 through 2.32. Asymmetrical blade sweep was investigated analytically in Reference 2.38.

Three references (2.2,2.3, and 2.36) indicated that fixed pitch propellers must be replaced with variable pitch propellers to achieve noise reductions.

Table 4.2 summarizes the type of information contained in the references for Section 3.0 regarding engine exhaust mufflers. It can be seen that test results from various mufflers and design methods are well represented. The comprehensive test series by Davis and Czernecki is particularly instructive. The general information in Reference 3.2 provides an indication of the muffler performance in the late 1930's time period. The general information in Reference 3.11 shows the configurations of mufflers used on European airplanes and provides an indication of the certification noise achieved.

Table 4.3 summarizes the approximate reductions in flyover noise that should be possible based on the information reviewed in this report. Note that the reductions indicated assume that engine noise has been reduced so it is not a factor in total aircraft noise. Note also that the various reductions listed are not always additive. In addition, Table 4.3 indicates whether cost, weight, structural reliability/durability or performance is affected.

Most of the noise reduction concepts discussed above would have to be incorporated in a new propeller installation. In terms of retrofit of a fixed pitch propeller to reduce noise of an existing aircraft, only two of the above items are practical: 1) change from thick square blade tips to thin round blade tips; and 2) the use of proplets. If the airplane being retrofitted has a variable pitch propeller then increasing the number of blades and reducing the diameter is feasible in addition to the use of thin round tip blades and proplets.

5.0 RECOMMENDATIONS

It is obvious that the manufacturers of propeller driven airplanes would design for reduced noise if there were no penalties. In fact, there are many penalties associated with lower noise propeller installations including cost, weight, structural reliability and performance.

Cost penalties are the result of increasing the number of blades, introducing variable pitch on fixed pitch installations, reducing RPM, and using unusual configurations such as proplets or asymmetrical blade spacing. Weight penalties are also the result of increasing the number of blades and reducing RPM. Structural reliability may be affected as number of blades is increased while attempting to maintain performance using narrower and thinner blades. The structural reliability may also be affected as blades are made thinner, are rounded at the tip, of if sweep is introduced at the blade tip. Performance penalties occur when the number of blades is increased, the RPM is reduced, or the diameter is reduced.

Furthermore, if some significant propeller noise reduction is achieved, then the engine noise becomes a factor in the total aircraft noise. This requires the installation of mufflers or some other engine noise suppressor which increases cost and weight and may affect engine performance.

The noise reduction payoff and penalties for the various concepts were summarized in Table 4.3. Based on this, it appears that the highest priority should be given to reducing the penalties for reducing RPM and propeller diameter while increasing the number of blades. In conjunction with this, overcoming the penalties for (1) replacing a fixed pitch with variable pitch propeller; and (2) adding an engine muffler(or using another engine noise suppression strategy) should also be high priority tasks.

Overcoming the penalties of increasing the number of blades and reducing propeller diameter requires investigating the use of new materials such as composites (including wood/fiberglass) to reduce weight. To reduce cost or hold cost constant, new innovative fabrication techniques must be explored. To maintain performance, new airfoils tailored specifically to low tip speed propellers must be developed.

To reduce propeller RPM, new efficient innovative and reliable low cost engines are required that inherently operate at low output RPM. Several possibilities are suggested for exploration:

- Oversize the displacement of existing aircraft engines and derate to produce maximum horsepower at reduced RPM. Investigate means to eliminate any penalties in fuel efficiency and weight of this concept.

- Develop aircraft versions of automotive engines with reliable output gearboxes or belt drives for low output RPM.

- Develop reliable gearbox systems for existing aircraft engines based on past experience and recent advances.

Efforts to reduce the cost, weight, and complexity of variable pitch propellers are needed. For retrofit of fixed pitch installations, a "bolt-on" system that automatically changes pitch as operating condition changes, would be desirable. Considering the advances made in composite materials, this might be accomplished with a flexible blade that changes pitch as RPM and flight speed changes. Also, systems like those developed in the past, in Europe, with propeller hubs incorporating self contained hydraulically actuated variable pitch controls might be considered.

It appears that muffler technology is well developed at this time. The problem for aircraft is to design practical mufflers that have a low back pressure and are small enough to fit within the engine enclosure while reducing A-Weighted noise level. Also the cost and durability of these mufflers should be addressed. For retrofit of existing airplanes, these are difficult tasks but should be conducted. Overcoming the experience in Europe where mufflers are often mounted outside the fuselage and cause a loss in airplane performance, should be a high priority. In new airplane designs, space should be made available for mufflers.

If the number of blades is increased to 4 or 6 and variable pitch can be incorporated in low noise propeller designs, then the use of asymmetrical configurations should also be investigated as a means for noise reduction. The theory and experiments with this concept show that some additional noise reduction should be possible with no additional penalties or complication.

In conclusion, any work based on the above recommendations should emphasize practical application. Also, the other noise reduction concepts of Table 4.3 should be considered in any propeller aircraft design tradeoff study in order to achieve the lowest noise on the basis of a system optimization.

ACKNOWLEDGEMENTS

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Table 2.1 CHARACTERISTICS OF STANDARD AND MODIFIED RECONNAISSANCE AIRCRAFT PROPULSION SYSTEMS

		Standard	Modified
Engine	Type	Horizontally Opposed	Horizontally Opposed
	Number of Cylinders	6	6
	Drive	Direct	Geared
	Horsepower	185	200
	Final Output RPM	2550	1000
	Exhaust System	Collector Stacks	Tuned Chamber Muffler
Propeller	Number of Blades	2	5
	Diameter	85 Inches	96 Inches
	Blade Planform	Narrow Tapered	Wide Paddle Blades
	Blade Tip	Elliptical	Elliptical

TABLE 2.2 SUMMARY OF STINSON AND CUB TESTS (REF. 2.2)

	<----------STINSON TEST CONFIGURATIONS---------->									CUB CONFIG.	
Configuration	1 &5	2A	2B	2C	2D	2E	2F	2G	2H	STD.	Mod.
Max 40 dB Noise Level 500 ft Flyover	82	70-72	69-71	68-63	65	70	65-69	65-70	68	70	61-62
Horsepower	153	183	181	183-153	179	181	183-153	179-153	157	63	80-63
Aircraft Weight in Lbs	1592	--	--	1591	--	--	1592	1593	1592	1177	1177
Avg. Takeoff Run in ft.	412	--	--	471	--	--	445	449	500	343	277
# of Blades	2	2	3	6	8	4	4	4	4	2	4
Blade Config.	Skyblade Wood	Wide	Med.	Thin	--	Thin	Med.	Wide	Solid	Wood	2 Piece Wood
Gear Ratio	1.00	.632	.632	.632	.632	.632	0.632	0.632	.632	1.00	0.632
Prop. Diameter Inches	76	84.5	76	76	76	76	76	84.5	76	72	80
Engine RPM	2600	3100	3050	3100	3000	3050	3100	3000	2650	2250	2550
Prop Tip Speed in Ft/Sec	862	720	638	645	627	638	645	697	554	707	562

TABLE 2.3 SUMMARY OF PUSHER AMPHIBIAN TESTS (REF. 2.3)

Parameter	Data							
Configuration	1	6	7	8	9A	9B	9C	9D	10
Aircraft Type	Std. Tractor	Std. Pusher	Std. Pusher	Mod. Pusher	Mod. Pusher	Mod. Pusher	Mod. Pusher	Mod. Pusher	Mod. Pusher
Muffler	No	No	No	No	Yes	Yes	Yes	Yes	Yes Relocated
# of Blades	2	2	4	4	3	4	6	6	8
Dia. in Inches	76	78	68	78	78	78	78	78	78
Pitch Control	Fixed	Variable	2 Fixed Angles	2 Fixed Angles	2 Fixed Angles	2 Fixed Angles	2 Fixed Angles	2 Fixed Angles	2 Fixed Angles
Engine RPM	2600	2600	2750	2500	2500	2500	2500	2500	2500
Horsepower	155	145	145	140	140	145	145	140	140
Gear Ratio	1.00	1.00	1.00	0.632	0.632	0.632	0.632	0.632	0.632
Propeller Tip Ft./Sec.	862	885	815	537	537	537	537	537	537
Max 40 dB Noise 500 ft Flyover	83	72	70.5	68	67.5	63.5	66.7	67.5	67.5
Aircraft Wt. in Lbs.	--	1898	1892	1995	2005	2012	2014	2022	2028
Max Level Flight HP	--	145	145	140	145	145	145	140	145
Max Level Flight MPH	--	126	125	124	125	123	124	123	125
Avg. Takeoff Run in Ft.	--	499	779	565	554	569	560	553	566

TABLE 2.4 CHARACTERISTICS OF STANDARD AND MODIFIED DEHAVILLAND OTTER PROPULSIONS

		Standard	Modified
Engine	Type	Radial	Radial
	Number of Cylinders	9	9
	Drive	Geared	Geared
	Cruise RPM	1650	1650
	Exhaust System	Exterior Augmentor Tubes	Collector Ring and Tuned Chamber Muffler
Propeller	Number of Blades	3	5
	Diameter	10.83 Ft	12 Ft
	Propeller Cruise RPM	1100	550
	Blade Planform	Narrow	Wide Paddle Blades
	Blade Tip	Round	Rectangular

TABLE 2.5 AIRCRAFT CHARACTERISTICS (REF. 2.9)

AIRCRAFT	AIRFRAME		POWERPLANT						PROPELLER			
	GROSS WEIGHT, LB.	WING AREA, FT^2	NUMBER	TYPE	CYLINDERS	DISPLACEMENT, IN^3	TAKEOFF RATING HP/RPM	NORMAL RATING HP/RPM	DIAMETER, IN.	NO. OF BLADES	GEAR RATIO PROP:ENGINE	SOLIDITY PER BLADE (0.7 RADIUS)
O-1	2100	174	1	RECIP.	6	470	213/2600	190/2300	90	2	1:1	0.035
U-10	3000	231	1	RECIP.	6	480	295/3400	280/3000	96	3	77:120	.0295
O-2	4200	201	2	RECIP.	6	360	210/2800	210/2800	76	2	1:1	.034
OV-1	12148	330	2	TURBO-PROP.	—	—	1100 SHAFT H.P.	900 SHAFT H.P.	120	3	1:124	.038
A-6	55060	529	2	TURBO-JET	—	—	8500 LB. STATIC THRUST (100% RPM)	8000 LB. STATIC THRUST (96% RPM)	—	—	—	—

TABLE 2.6 SUMMARY OF 0-1 MODIFICATIONS (REF. 2.9)

CONFIGURATION	PROPELLER						MUFFLER [a]			TAIL-PIPE LENGTH FT.	NET WEIGHT INCREASE LB.	OVERALL SOUND PRESSURE LEVEL @ 300 FT. dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (0.7 RADIUS)	TYPE	DIA. & LENGTH IN.	VOLUME FT^3	LOCATION			
BASIC O-1A	1:1	2250	90	2	0.035	FIXED PITCH	—	—	—	—	—	95.2
MOD. I	1:1	2250	78	6	.0203	CONTROL'BLE PITCH	7.5×31.6	0.725	EXTERNAL [b]	1.67	25	84.7
MOD. I-REV.	1:1	2250	78	6	.0203	CONTROL'BLE PITCH	9.7×38.8	1.54	EXTERNAL [b]	1.67	34	82.1
MOD. II	2:3	1500	90	5	.035	CONTROL'BLE PITCH	9.7×38.8	1.54	INTERNAL [c]	2.89	115	78.7
MOD. III	1:2	1125	90	5	.056	CONTROL'BLE PITCH	19×26	6.15	INTERNAL [c]	2.89	255	74.2

[a] SINGLE - CHAMBER RESONATOR

[b] BENEATH FUSELAGE BETWEEN LANDING GEAR STRUTS

[c] INSIDE FUSELAGE AFT OF PASSENGER COMPARTMENT

TABLE 2.7 ESTIMATED SEA-LEVEL PERFORMANCE OF THE O-1 AIRCRAFT (REF. 2.9)

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II	MOD. III
GROSS WEIGHT, LB.	2100	2125	2215	2400[a]
TYPE OF PROPELLER (FIXED OR CONTROLLABLE PITCH)	FIXED	CONTROLLABLE	CONTROLLABLE	CONTROLLABLE
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	550	531	552	763
GROUND RUN, FT.	311	293	302	415
RATE OF CLIMB, FT/MIN.	1290	1300	1295	1090
MAXIMUM SPEED, KTS.	115.9	115.5	115.8	115
STALLING SPEED, KTS.	36.5	36.7	37.7	39.4
CRUISE SPEED, KTS.	78	80	80	80
SPEED FOR BEST RATE OF CLIMB, KTS.	58	58	59	60

[a] INCLUDES 45 LB. BALLAST AT TAIL POST TO KEEP AIRCRAFT CENTER OF GRAVITY WITHIN ALLOWABLE LIMITS

TABLE 2.8 SUMMARY OF U-10 MODIFICATIONS (REF. 2.9)

CONFIGURATION	PROPELLER					MUFFLER[a]		TAIL-PIPE LENGTH FT	NET WEIGHT INCREASE LBS	OVERALL SOUND PRESSURE LEVEL @ 300 FT dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (0.7 RADIUS)	DIA. & LENGTH IN	VOLUME FT^3			
BASIC U-10	77:120	1765	96	3	0.0295	—	—	—	—	97
MOD. I	77:120	1765	84	5	.0265	7.5×80	2	3.63	17	83
MOD. II	44:120	1008	108	5	.0274	7.5×80	2	3.63	100	78

[a] DOUBLE EXPANSION CHAMBER

TABLE 2.9 ESTIMATED PERFORMANCE OF THE U-10 AIRCRAFT (REF. 2.9)

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II
GROSS WEIGHT, LBS	3000	3017	3100
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	520	553	549
TAKE-OFF GROUND RUN, FT	236	252	246
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	1460	1408	1431
5000 FT.	1120	1079	1098
10 000 FT.	815	781	789
SERVICE CEILING @ NORMAL RATED POWER, FT.	21 100	20 700	20 700
SPEED FOR BEST RATE OF CLIMB, KTS, @ SEA LEVEL	80	85	81
5000 FT.	85	86	86
10 000 FT.	86	87	88
MAXIMUM SPEED, KTS, @ SEA LEVEL	143	143	144
5 000 FT.	141	141	142
10 000 FT.	139	139	139

TABLE 2.10 SUMMARY OF O-2 MODIFICATIONS (REF. 2.9)

CONFIGURATION	PROPELLER					MUFFLER		TAIL-PIPE LENGTH FT	NET WEIGHT INCREASE LB	OVERALL SOUND PRESSURE LEVEL @ 300 FT. dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (0.7 RADIUS)	DIA. & LENGTH IN.	VOLUME FT^3			
BASIC O-2	1:1	2400	76	2	0.034	a	0.45	0.42		92
MOD. IA	1:1	2400	64	6	.0215	12×36	2.22 [b]	1	16	82
MOD. IB	1:1	2400	64	6	.0215	13×46	3.33 [b]	2.65	43	80
MOD. II	3:4	1800	76	6	.018	d	3.49 [c]	1	117	78

a STANDARD EQUIPMENT ON REAR ENGINE ONLY, OVAL SHAPE APPROXIMATELY 4.6×12.6 IN., AND 16 IN. LONG
b SINGLE CHAMBER RESONATOR
c DOUBLE EXPANSION CHAMBER
d MUFFLERS FOR EACH ENGINE COMBINED INTO ONE PACKAGE HAVING OVAL CROSS SECTION (6.6× 19.8 IN) AND 120 IN. LONG

TABLE 2.11 ESTIMATED PERFORMANCE OF THE O-2 AIRCRAFT (REF. 2.9)

ITEM	BASIC AIRCRAFT	MOD. IA	MOD. IB	MOD. II
GROSS WEIGHT, LB.	4200	4216	4243	4317
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	1435	1505	1515	1500
TAKE-OFF GROUND RUN, FT.	805	840	850	860
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	1305	1270	1260	1270
5000 FT.	1010	975	970	986
10 000 FT.	715	680	675	685
SERVICE CEILING @ NORMAL RATED POWER, FT	20 500	20 000	20000	20300
SPEED FOR BEST RATE OF CLIMB, KTS, @ SEA LEVEL	93	93	94	94
5000 FT.	98	98	98	99
10 000 FT.	103	103	103	104
MAXIMUM SPEED, KTS., @ SEA LEVEL	174	172	172	172
5000 FT.	172	170	170	170
10 000 FT.	168	166	166	166

TABLE 2.12 SUMMARY OF OV-1 MODIFICATIONS (REF. 2.9)

Configuration	Propeller					Net Weight Increase LB	Overall Sound Pressure Level @ 300 FT. dB
	Gear Ratio Prop:Engine	Prop. RPM	Diameter IN.	No. of Blades	Solidity per Blade (0.7 Radius)		
Basic OV-1	1:12.4	1200	120	3	0.0381	—	93.3
Mod. I	1:12.4	1200	108	5	.0343	−22	81.5
Mod. II	1:16.53	900	120	5	.0381	129	77.1
Mod. III	1:17.71	840	120	6	.0343	82	75.2

TABLE 2.13 ESTIMATED PERFORMANCE OF THE OV-1 AIRCRAFT (REF. 2.9)

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II	MOD. III
GROSS WEIGHT, LB	12 148	12 126	12 277	12 230
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	1 073	1 116	1 165	1 146
TAKE-OFF GROUND RUN, FT.	723	765	810	783
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	2416	2383	2325	2328
10 000 FT.	1748	1713	1668	1671
20 000 FT.	995	976	935	943
SERVICE CEILING, FT.	29 300	29 300	28 800	28 800
SPEED FOR BEST RATE OF CLIMB, KTS., @SEA LEVEL	139	139	139	139
10 000 FT.	144	144	146	145
20 000 FT.	156	156	157	157
MAXIMUM SPEED, KTS., @ SEA LEVEL	242	242	241	241
10 000 FT.	249	249	248	248
20 000 FT.	245	245	244	244

TABLE 2.14 SUMMARY OF ACOUSTIC FLIGHT TEST RESULTS ON THE PIPER LANCE (REF. 2.9)

SERIES	MODE/RPM/POWER/TAS	M_H	INFLOW ANGLE (DEGREES)	SHP	GROUND MINUS ELEVATED MICROPHONES (ALM)	EXHAUST CONTRI-BUTION TO ALM	PROP ONLY PRIMARY GROUND	PROP ONL PRIMARY 4 FT.
A	TO/2780/96%/82	0.873	4.3°	287	2.5	0.2	91.7	89.4
B	TO/2780/96%/95	0.875	1.2°	287	2.5	0.3	91.1	88.7
C	TO/2780/96%/123	0.882	-2.2°	287	2.5	0.3	90.2	87.8
D	LFO/2780/96%/167	0.896	-4.4°	287	2.3	0.4	89.4	87.2
E	TO/2780/77%/82	0.868	4.0°	231	2.5	0.2	90.3	87.8
F	TO/2780/77%/96	0.870	0.9°	231	2.6	0.3	89.6	87.1
G	TO/2780/77%124	0.876	-2.2°	231	2.2	0.3	88.9	87.0
H	LFO/2780/77%/152	0.886	-3.9°	231	2.1	0.3	88.4	86.5
I	TO/2570/55%/95	0.804	1.2°	165	2.3	1.0	79.8	77.9
J	TO/2570/55%/123	0.812	-2.2°	165	2.2	1.8	78.7	76.6
K	TO/2640/77%/97	0.824	0.6°	231	2.2	0.9	83.5	81.4
L	LFO/2630/77%/153	0.837	-3.8°	231	1.8	1.0	81.8	80.6
M	TO/2440/77%/97	0.762	0.6°	231	2.0	1.6	77.5	75.9
N	LFO/2460/77%/150	0.785	-3.6°	231	2.C	1.7	77.2	75.5
O	TO/2240/77%/97	0.700	1.5°	231	2.2	3.9	73.8	71.8
P	TO/2320/55%/94	0.723	1.9°	165	2.0	2.6	73.7	71.8
Q	TO/2140/55%/95	0.669	1.9°	165	2.2	3.6	70.7	69.0

TABLE 2.15 CHARACTERISTICS OF STANDARD AND REPLACEMENT PROPELLERS (REF. 2.29)

	Super King Air 200		DHC6-300Twin Otter	
	Standard	Replacement	Standard	Replacement
-Number of Blades	3	4	3	4
-Diameter, inches	98.5	94.0	102.0	93.0
-Blade Material	Aluminum	Aluminum	---	---
-Hub Material	Steel	Aluminum	---	---
-Total Installed Weight	140 lb	151 lb	---	---
-1000 ft Max Power Max RPM Flyover Noise dBA	79.2	75.0	77.4	72.3

TABLE 2.16 GEOMETRIC DATA FOR THE TEST PROPELLERS (REF. 2.29)

Propeller Config.	Diameter (m)	Number of blades	Solidity %	Propeller Mass (kg)
2	1.927	2	8.6	18.5
3	1.825	3	11.4	20.0
4	1.735	4	13.9	17.0
5	1.637	5	18.5	20.5
6	1.534	6	23.3	25.0

TABLE 3.1 DATA FROM AIR COMMERCE BULLETIN TESTS

Sound Level at a Distance of 80 Feet(Decibels above 10^{-14} Watts per cm^2)

(REF. 3.1)

	Levels With Frequency Band Filters					
Configuration	None	0 to 250	250 to 500	500 to 1500	1500 to 3000	3000 to ∞
Open Ports	83	63	53	67	78	77
B.S. 1	67	60	47	52	62	60
B.S. 3	68	59	53	55	63	64
Side Manifolds	75	72	53	61	68	66
Burgess (bulk absorber)	73	72	54	56	58	51
Corless (spinning rotor)	64	61	50	49	57	56
Manifolds Collected to Single Exhaust Pipe	69	61	52	58	63	64
B.S. 2	65	60	55	52	53	53
Sikorsky (resonator)	66	62	49	53	60	59
Watson (wire mesh)	64	56	48	54	57	56
Wolford (3 cavities in series)	69	61	55	54	61	62
Rowan Large	64	--	--	--	--	--
Rowan Small	63	--	--	--	--	--
Barrels(underground)	57	50	40	47	52	48

TABLE 3.2 PERFORMANCE OF MUFFLERS TESTED BY PEGG AND HILTON

(REF. 3.6)

		Noise Reduction in dB at Harmonics of Firing Frequency						
Muffler	Operating Power kw	1	2	3	4	5	6	>6
A	173	25	19	23	26	25	15	~7-10
B	173	23	19	25	30	26	15	~7-10
C	120	23	5	22	18	18	16	~5-12
D	120	11	9	17	10	15	7	~3-15
E	129	13	5	13	12	8	8	~0-11

TABLE 4.1 PROPELLER NOISE REDUCTION CONCEPTS CONSIDERED IN THE LITERATURE

Ref. No.	Author	Date	Noise Reduction Concepts Discussed							
			Reduce RPM	Reduce Diam	Incr. Diam.	Incr. # of Blades	Sweep	Tip Geometry	Passive Exhaust Muffler	Other
2.1	Vogeley	1948	T	T	T				T	
2.2	Beranek, et al	1950	T			T		T	T	9
2.3	Roberts & Beranek	1952	T		T	T		T	T	9
2.4 - 2.5	Johnston & Law	1957-1958	T		T	T		T	T	
2.6 - 2.7	Hoffman & Muhlbauer	1974	O	O		O				
2.8	Harlamert	1974	X			X		X		
2.9 - 2.13	Dingledein/ Hilton/ Conner	1975	T	T	T	T			T	
2.14	Rathgeber & Sipes	1977	T					T		
2.15	Muhlbauer	1978		T		T				
2.16	Masefield	1978	T*							
2.17	Wilby & Galloway	1979	O	O		O			O	
2.18	Davis	1979	C	C						1
2.19-2.20	Klatte & Metzger	1979-1981		C		C	C	C	C	1
2.21	Borchers	1980				T				2
2.22	Korkan et al	1980	C	C		C	C	C	C	3,4
2.23	Sullivan et al	1981								2,3
2.24	Succi	1981		T					T	
2.25	Gregorek et al	1983		T		T				1

Ref. No.	Author	Date	Noise Reduction Concepts Discussed							
			Reduce RPM	Reduce Diam	Incr. Diam.	Incr. # of Blades	Sweep	Tip Geometry	Passive Exhaust Muffler	Other
2.26	Salikuddin et al	1984								5
2.27	Dobrzynski	1986	T*					T		6
2.28	Jones	1986	T						**	6
2.29	Raisbeck & Mills	1987		T						
2.30-2.32	Dobrzynski	1990-1993								7
2.33-2.35	Kallergis	1990-1993								8
2.36	Weiblen	1992	T	T		T		T		1,9
2.37	Dobrzynski	1993		T		T				
2.38	Lohmann	1993								10
2.39	Chusseau et al	1993		C		C		C		
2.40	Cox	1995	O	O		O		O	O	

Key:

T: Test
C Calculation
O: Opinions
*: Reduced Tip Mach Number
**: Engine Noise Contribution

Other Noise Reduction Concepts

1 Improved Propeller Efficiency
2 BiBlade Propeller
3 Proplets
4 Airfoil Chordwise Pressure Loading
5 Active Noise Cancellation
6 Angle of Attack
7 Asymmetric Blade Spacing
8 Noise Cancellation by Exhaust
9 Replace Fixed with VP Prop
10 Asymmetric Blade Sweep

TABLE 4.2 TYPE OF INFORMATION IN MUFFLER REPORTS

Ref.	Author	Date	Test Data	Design Method	General Information
3.1	Air Commerce Bulletin	1932	X		
3.2	London	1940			X
3.3	Czernecki & Davis	1948	X	X	
3.4	Davis & Czernecki	1949	X		
3.5	Parrott	1973		X	
3.6	Pegg & Hilton	1974	X		
3.7	Maglieri & Hubbard	1975	X		
3.8	Sullivan	1979	X	X	
3.9	Munjal	1987		X	
3.10	Galaitis & Ver	1992		X	
3.11	Gomolzig	1995			X

TABLE 4.3 PENALTIES FOR VARIOUS NOISE REDUCTION CONCEPTS

	Penalties to Be Overcome				
Noise Reduction Concept	Cost Increase	Weight Increase	Structural Reliability	Performance Reduction	Noise Reduction Potential
Reduce RPM & Diameter Increase # of Blades	X	X	X	X	H
Reduce RPM & Increase Diameter	X	X			L to M
Increase # of Blades	X	X	X	X	M
Sweep Blade Tips	X		X		L
Change Tip Geometry			X	X	L to M
Reduce Tip Load				X	L to M
Use BiBlades	X	X	X		L
Use Proplets	X		X		L
Change Airfoil Chordwise Pressure				X	L
Use Active Noise Cancellation	X	X			L to M
Change Angle of Attack					L
Use Asymmetrical Blade Spacing	X	X			L to M
Cancel Prop Noise with Exhaust Noise	X	X			L to M
Replace Fixed Pitch with Variable Pitch Prop.	X	X			M
Use Asymmetric Blade Sweep	X		X	X	M
Add an Engine Muffler	X	X		X	M

Key to Symbols:

H:	high noise reduction potential	(5 to 8 dBA reduction)
M:	medium noise reduction potential	(3 to 5 dBA reduction)
L:	low noise reduction potential	(1 to 3 dBA reduction)

Standard Modified

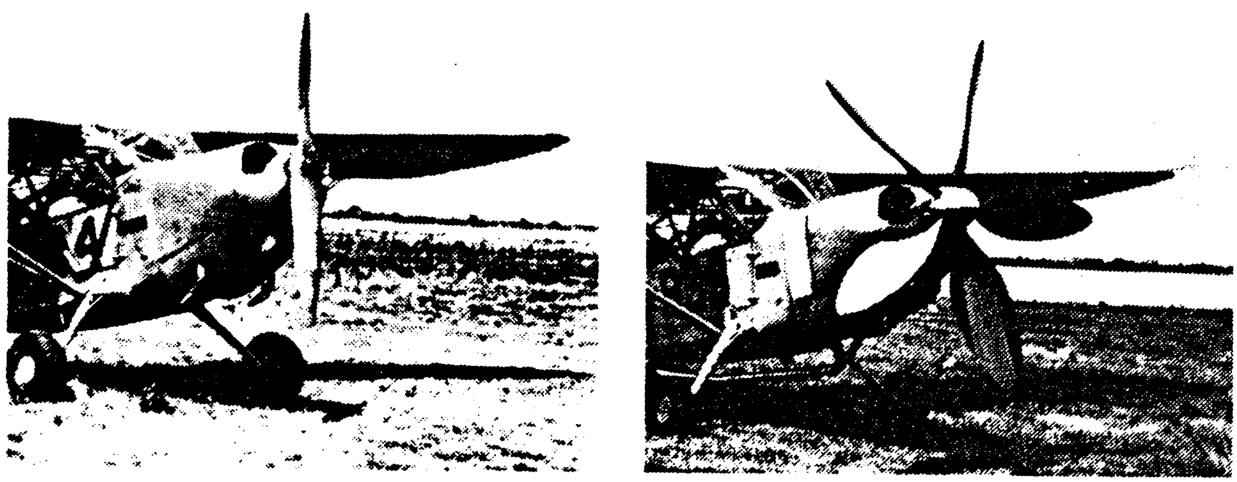


FIGURE 2.1 Comparison of Standard and Modified Reconnaissance Aircraft (Ref. 2.1)

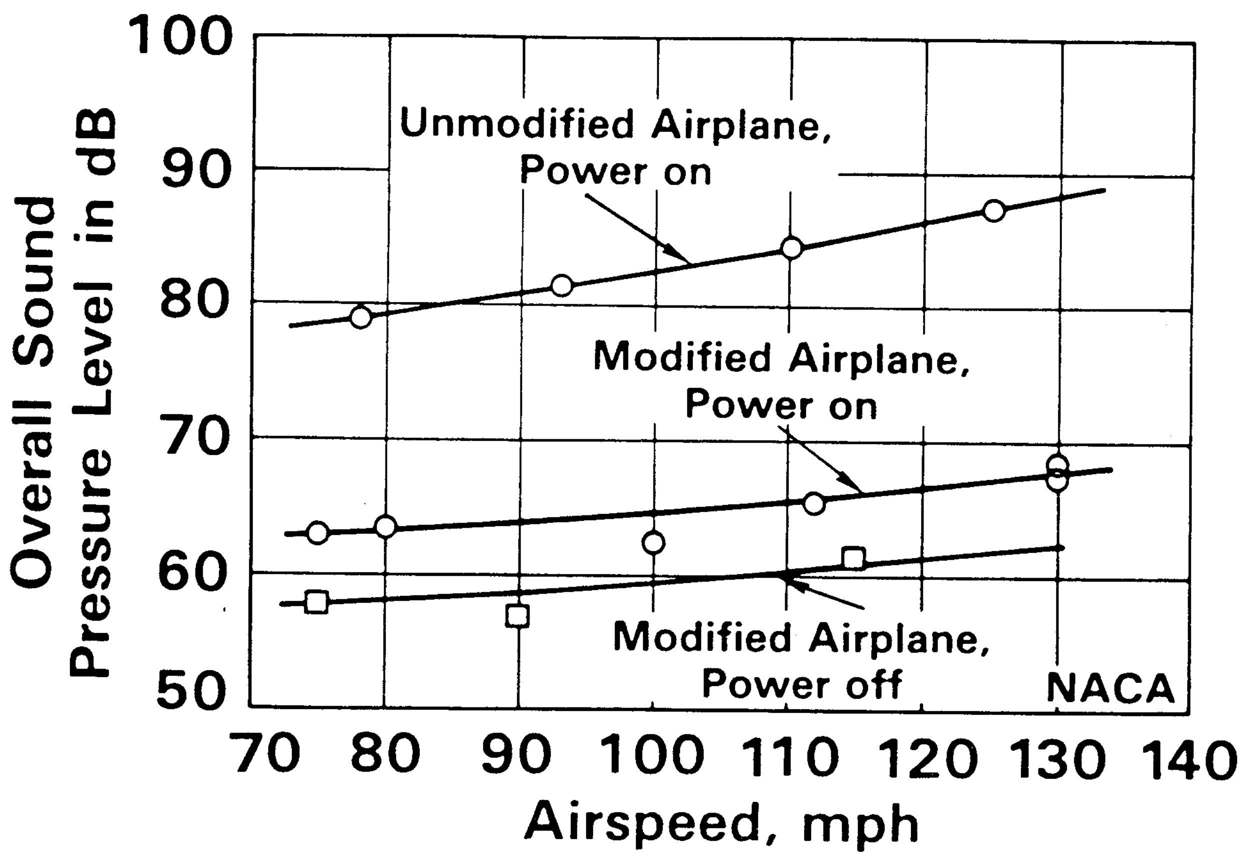


FIGURE 2.2 Noise Characteristics of Standard and Modified Reconnaissance Aircraft at 300 Ft. Altitude (Ref. 2.1)

FIGURE 2.3 Standard Stinson Configuration 1 (Ref. 2.2)

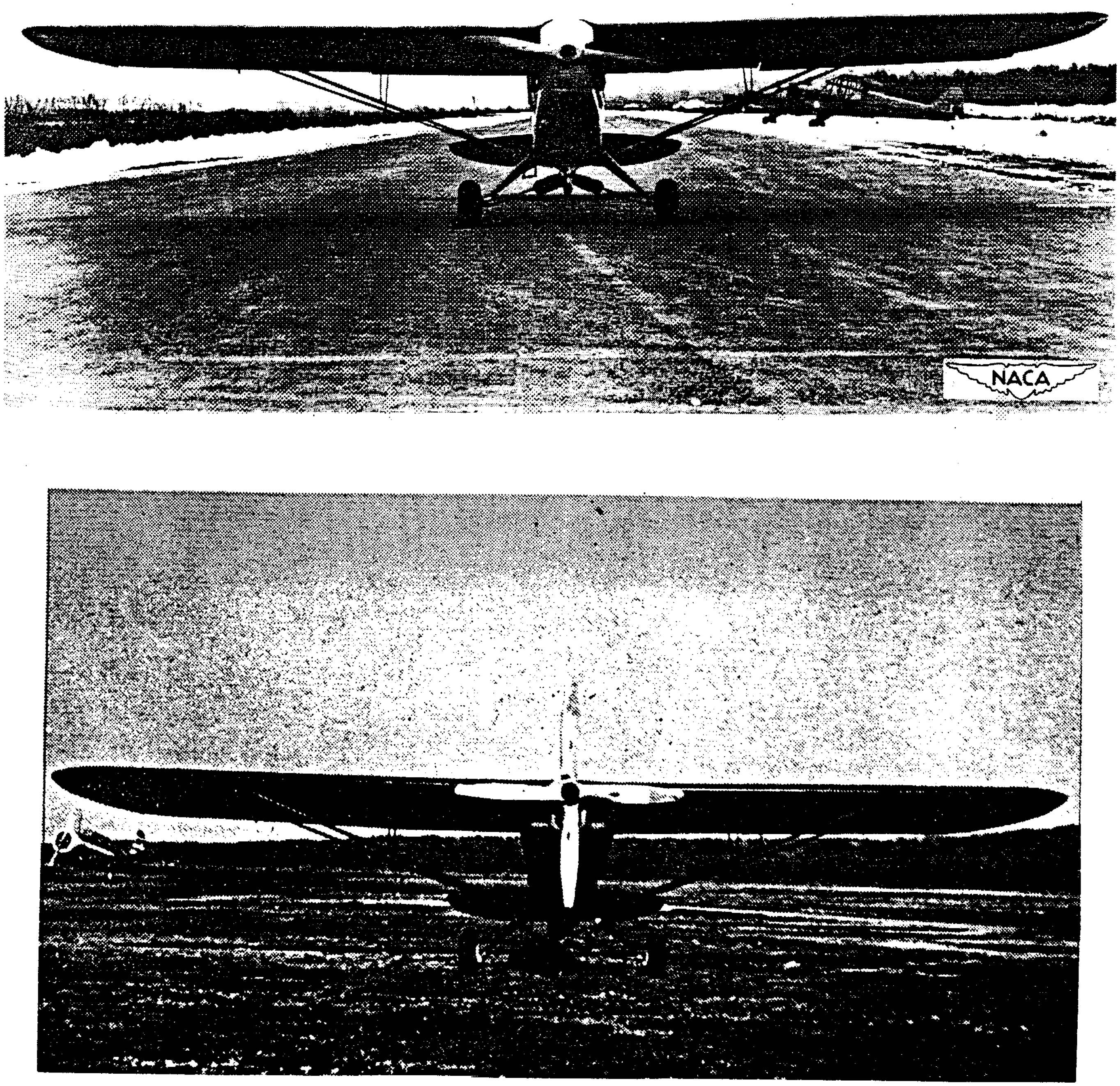


FIGURE 2.4 Standard (top) and Modified (bottom) Cub (Ref. 2.2)

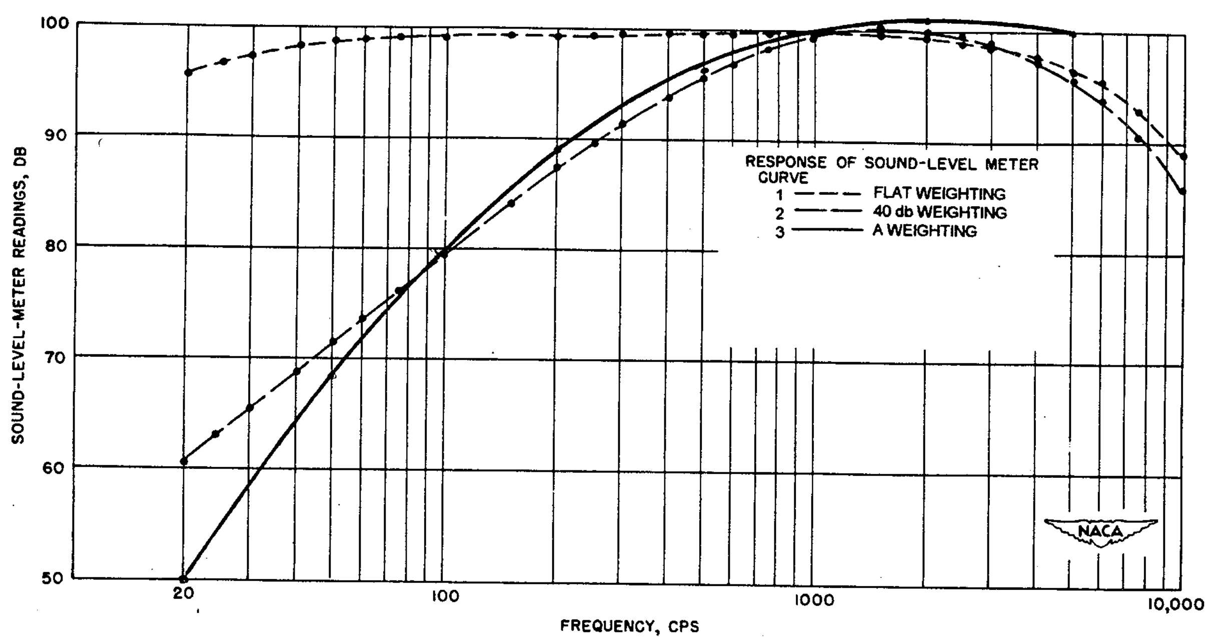


FIGURE 2.5 Comparison of 40 dB Weighting and A-Weighting (Ref. 2.2)

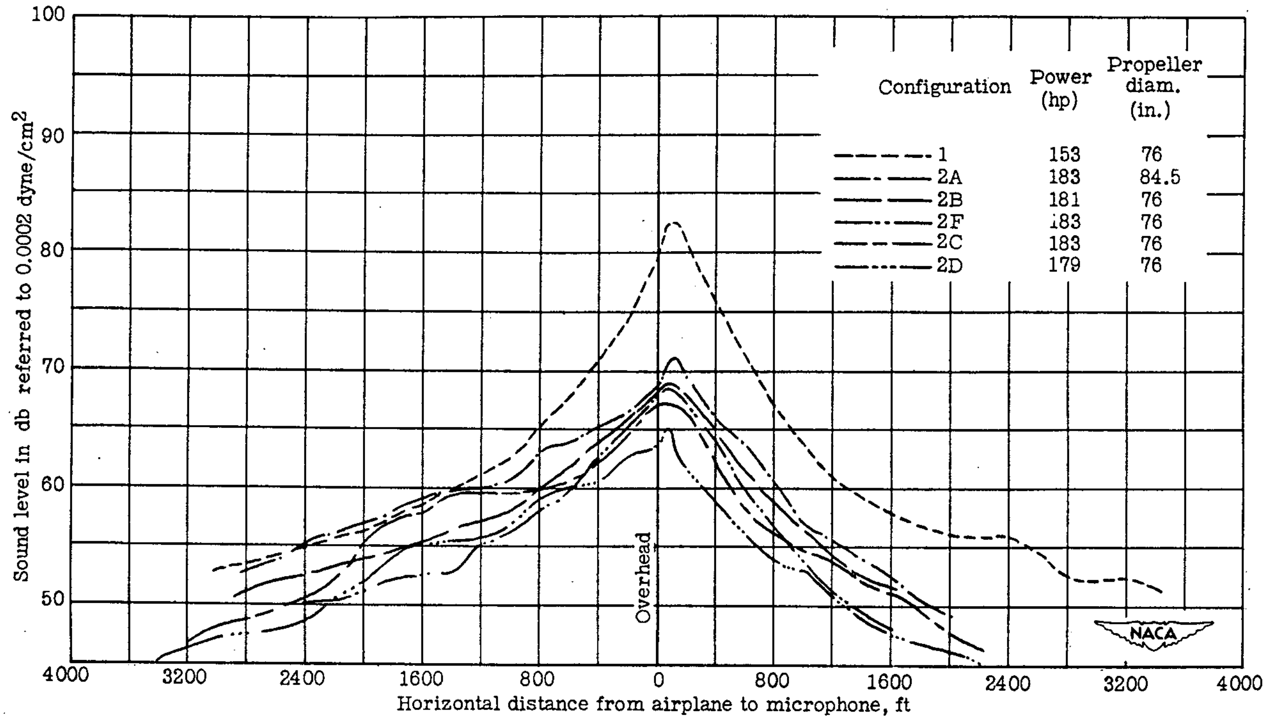
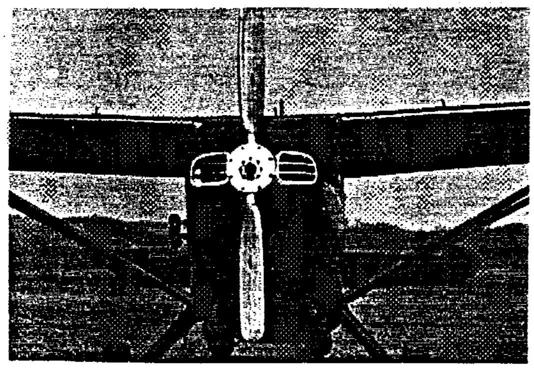
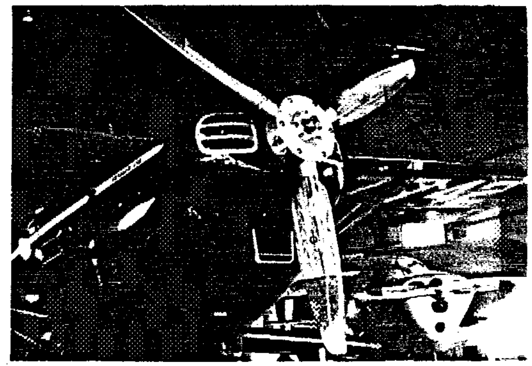


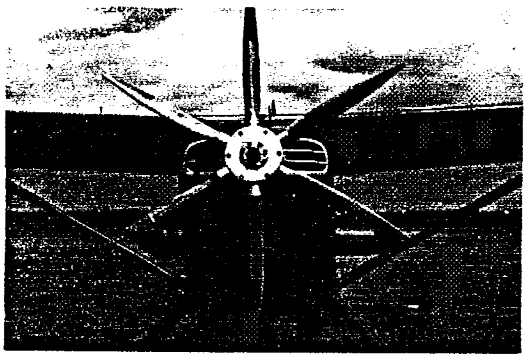
FIGURE 2.6 Average Curves of Sound Level Versus Distance for Flyover of Six Configurations of the Stinson Airplane (Altitude 500 ft, max power, 40 dB weighting) (Ref. 2.2)



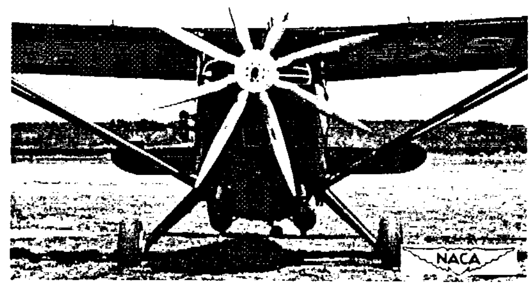
(a) Two-bladed propeller, configuration 2A.



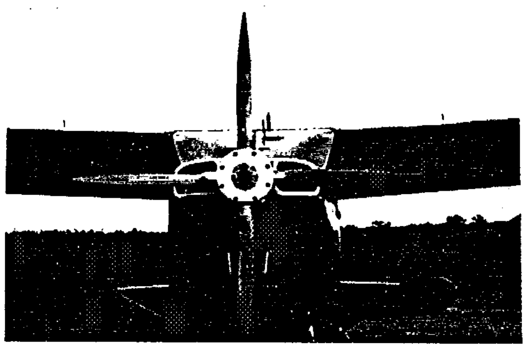
(b) Three-bladed propeller, configuration 2B.



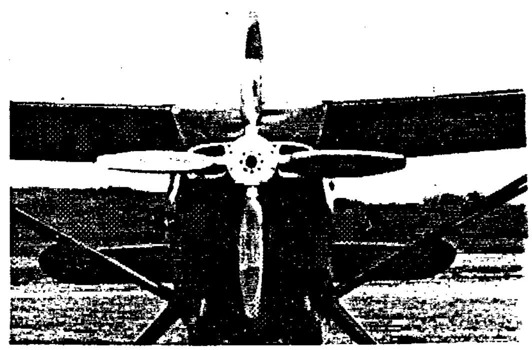
(c) Six-bladed propeller, configuration 2C.



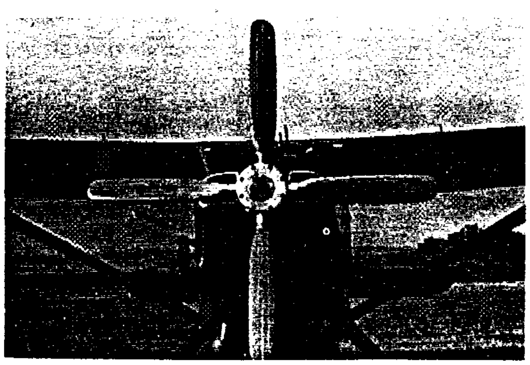
(d) Eight-bladed propeller, configuration 2D.



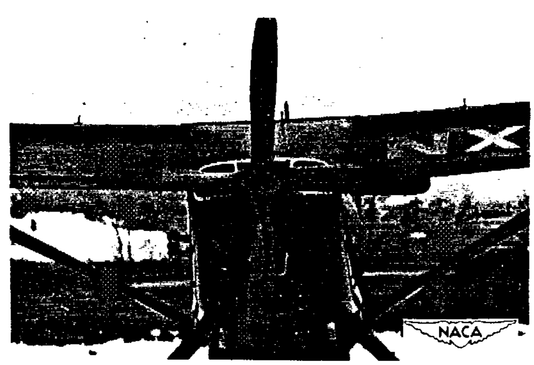
(e) Thin-bladed propeller, configuration 2E.



(f) Medium-bladed propeller, configuration 2F.

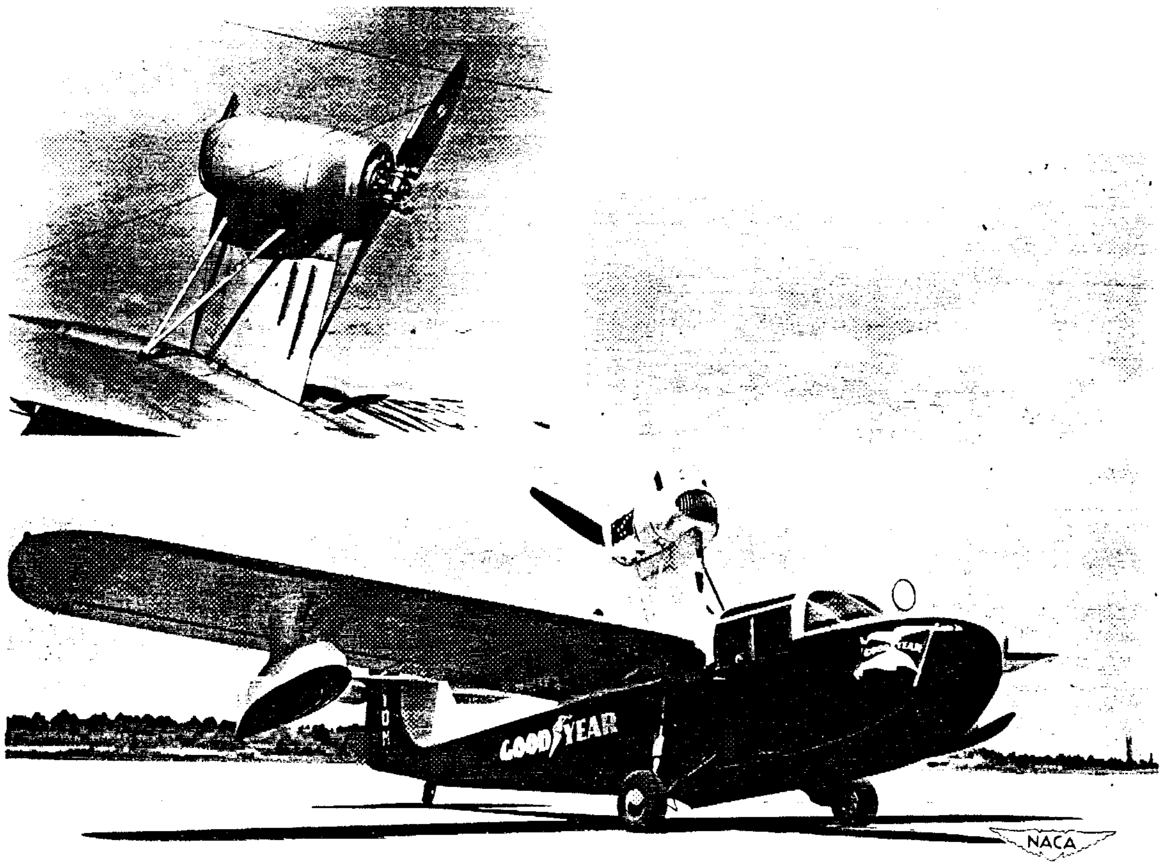


(g) Wide-bladed propeller, configuration 2G.



(h) Solid-bladed propeller, configuration 2H.

FIGURE 2.7 Stinson Propeller Configurations (Ref. 2.2)



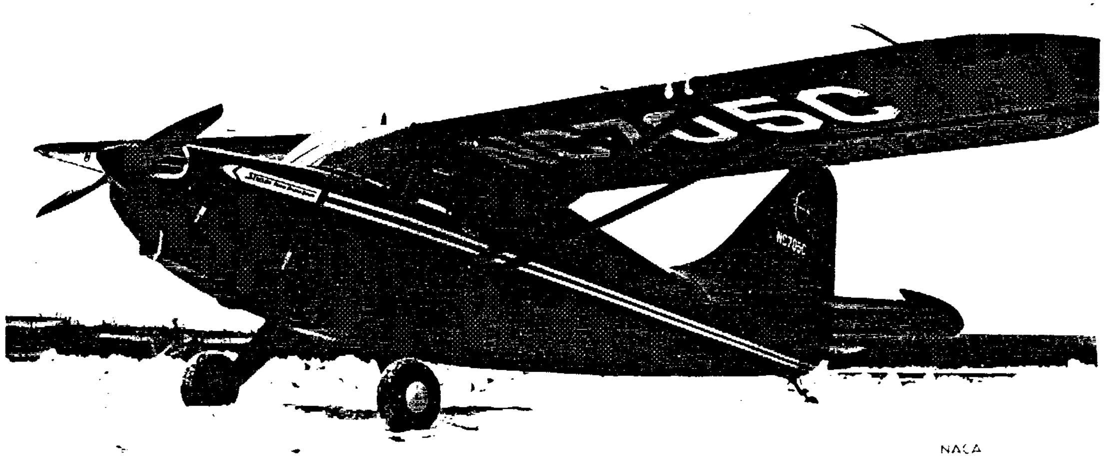


FIGURE 2.8 Standard Pusher - Type Amphibian (top) and Standard Tractor Configuration (bottom) (Ref. 2.3)

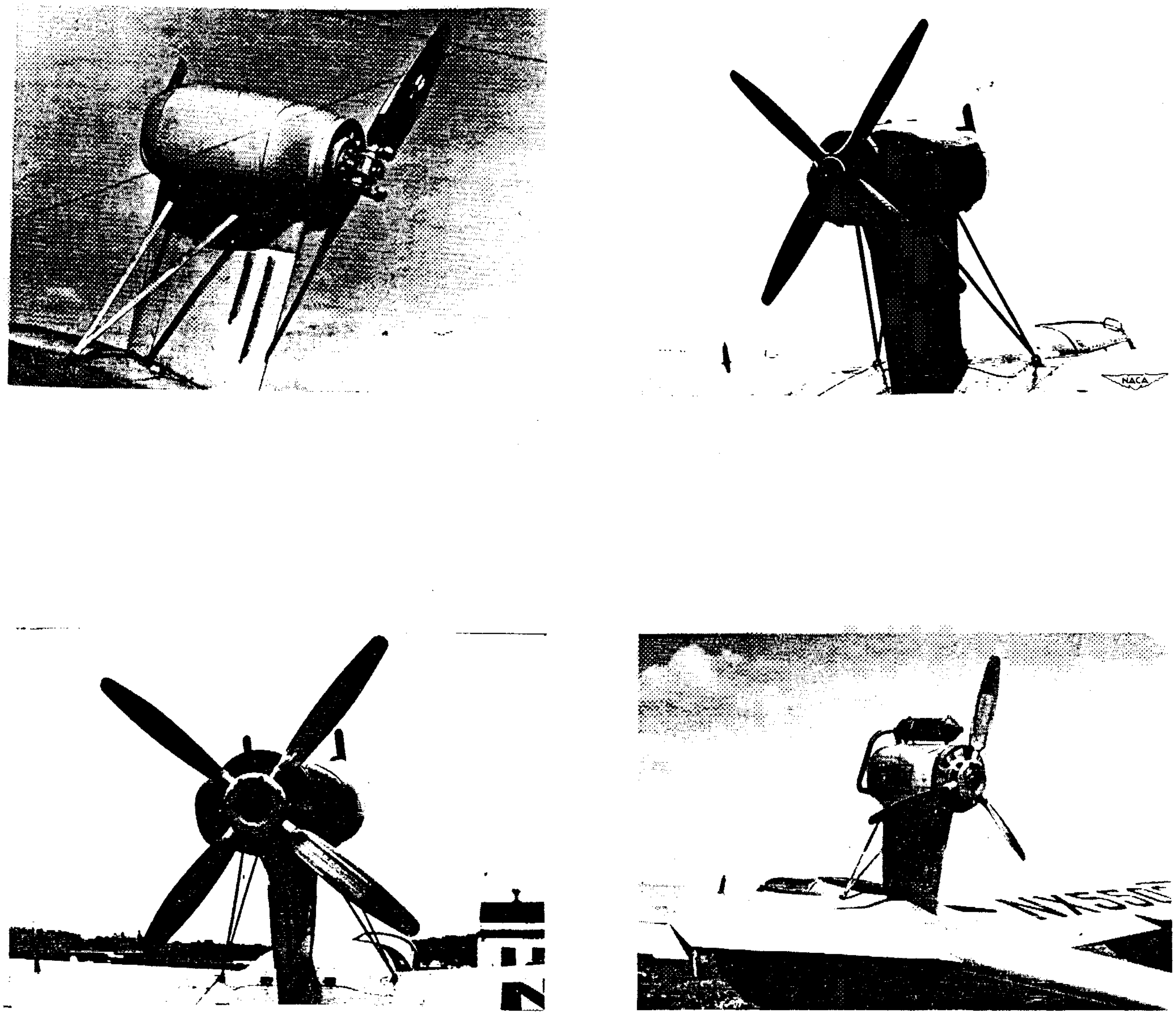


FIGURE 2.9 Modified Amphibian Propeller Configurations (Configuration 6 Upper Left, Configuration 7 Upper Right, Configuration 8 Lower Left, Configuration 9A Lower Right) (Ref. 2.3)

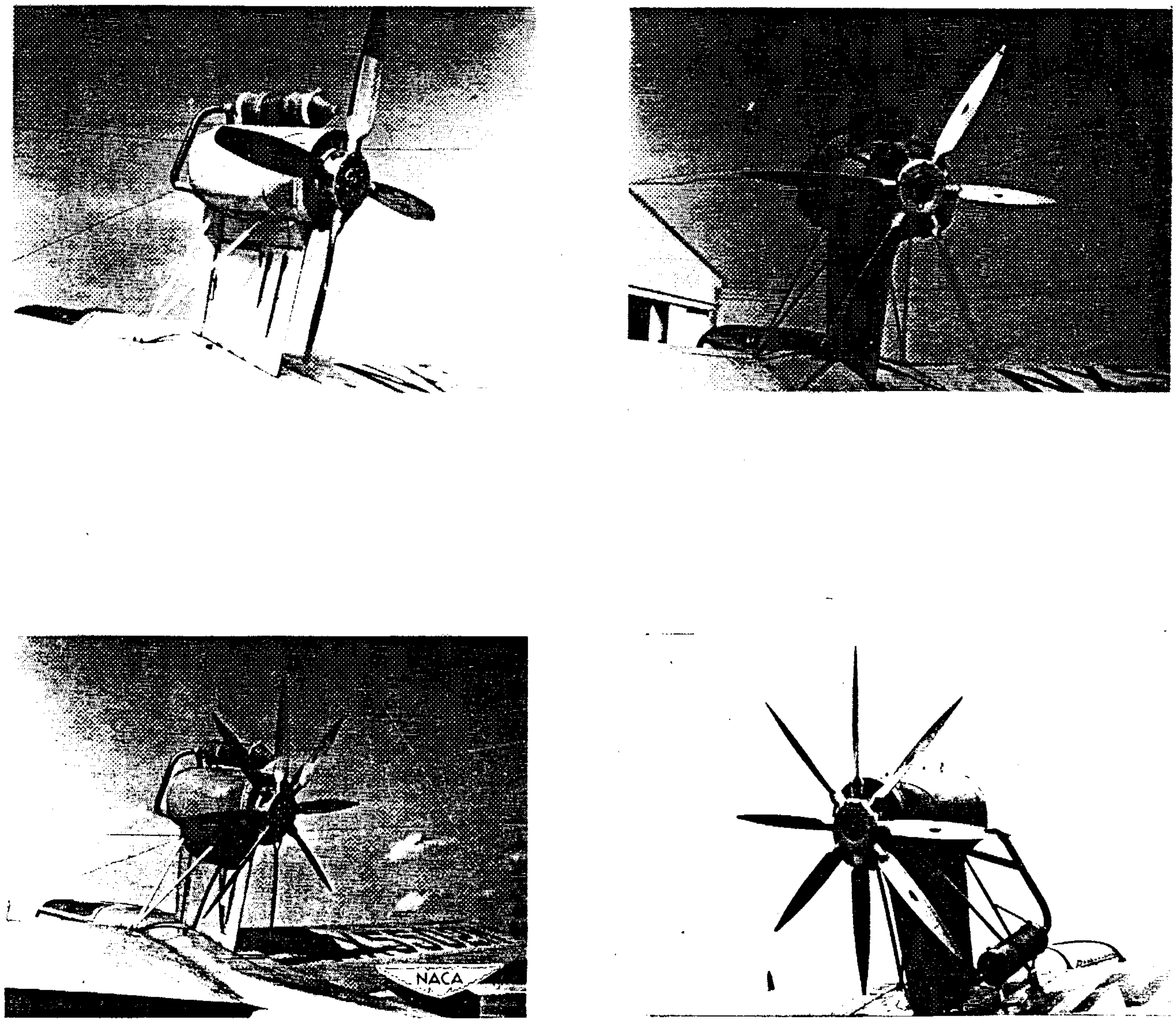


FIGURE 2.10 Modified Amphibian Propeller Configuration (Configuration 9B Upper Left, Configuration 9C Upper Right Configuration 9D Lower Left, Configuration 10, Lower Right) (Ref. 2.3)

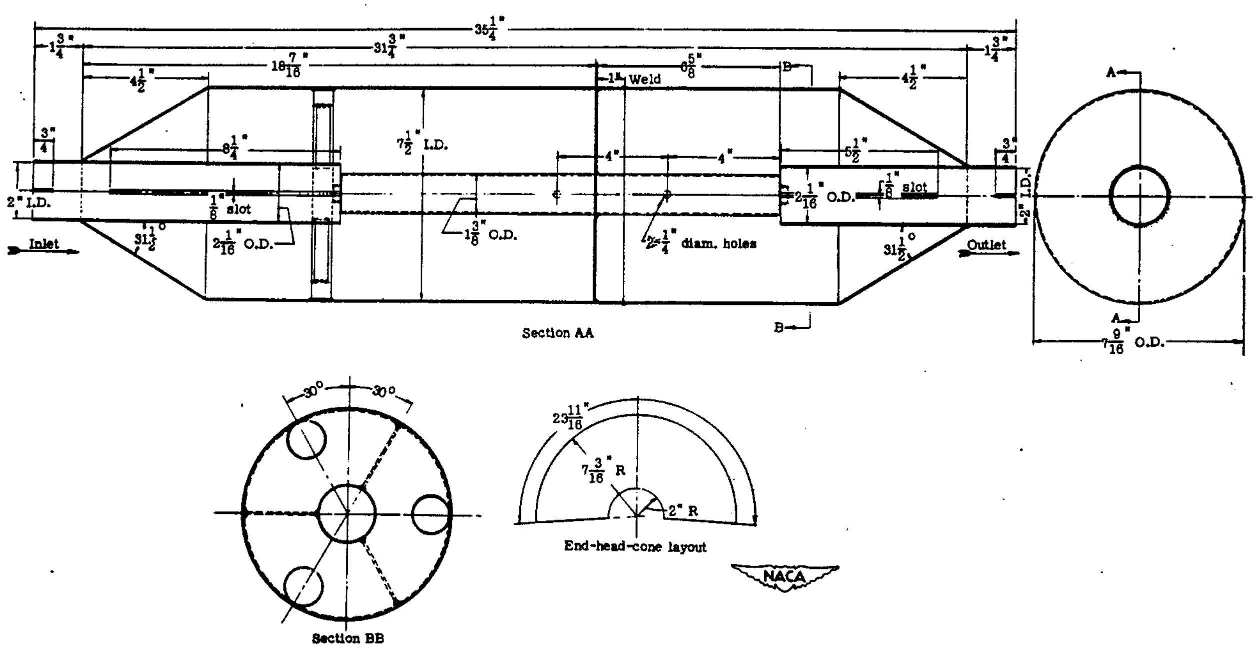


FIGURE 2.11 Maxim Silencer Used on the Modified Amphibian (Ref. 2.3)

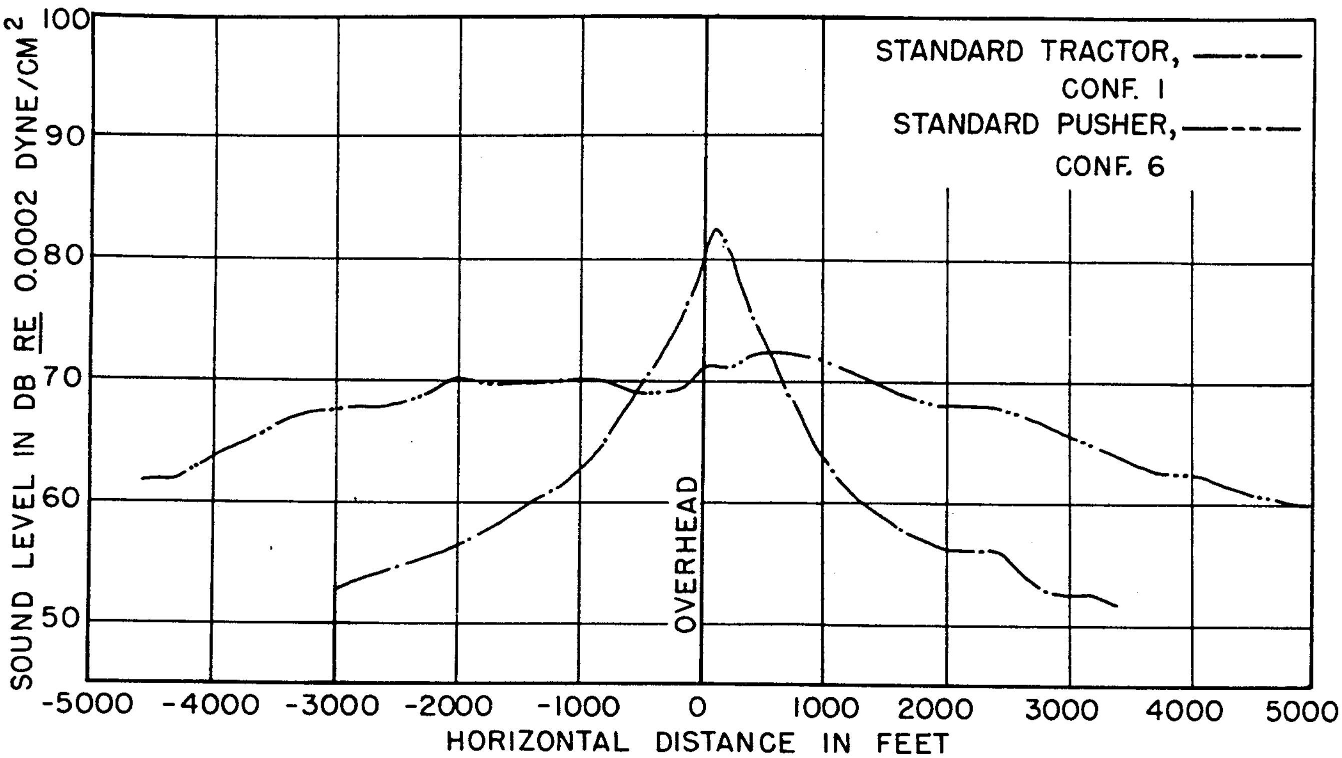


FIGURE 2.12 Comparison of 40 dB Weighted Flyover Noise for the Standard Tractor and Standard Pusher (Ref. 2.3)

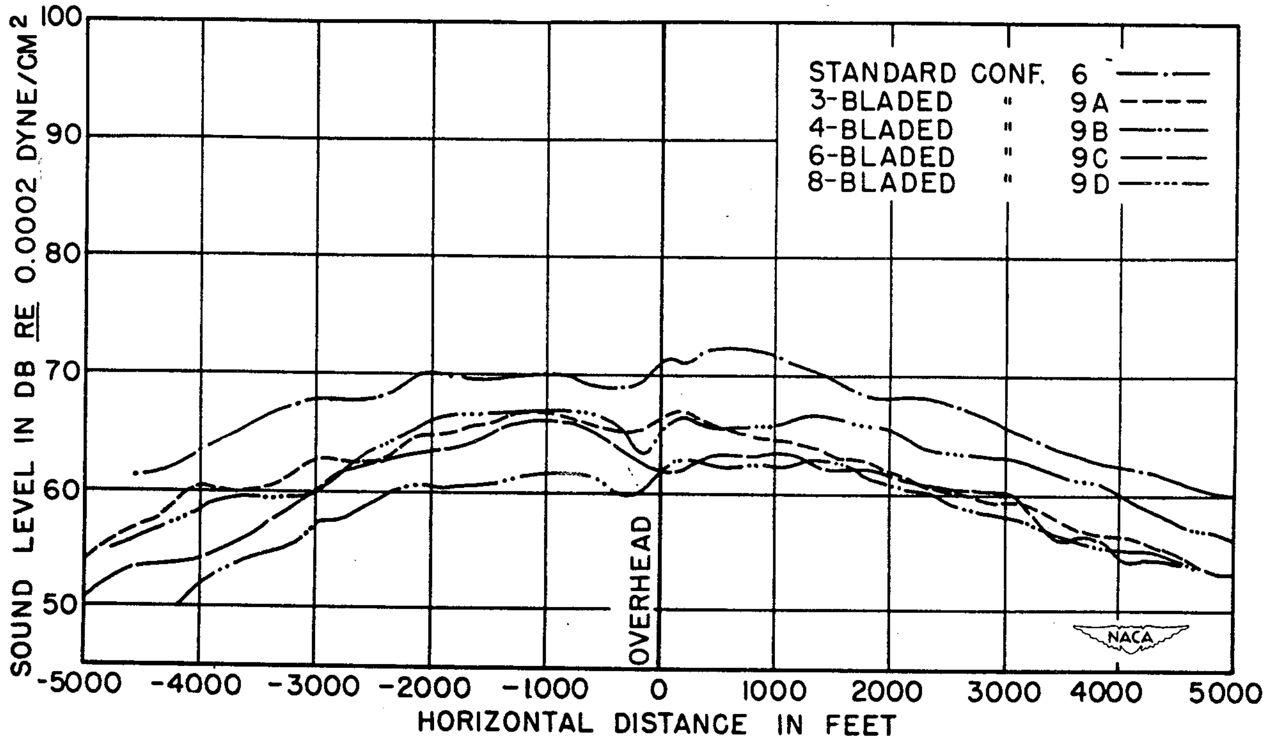


FIGURE 2.13 Average Curves of Sound Level Versus Distance for Flyover of Five Configurations of the Pusher Amphibian (Altitude 500 ft, max power, 40 dB Weighting) (Ref. 2.3)

Standard **Modified**

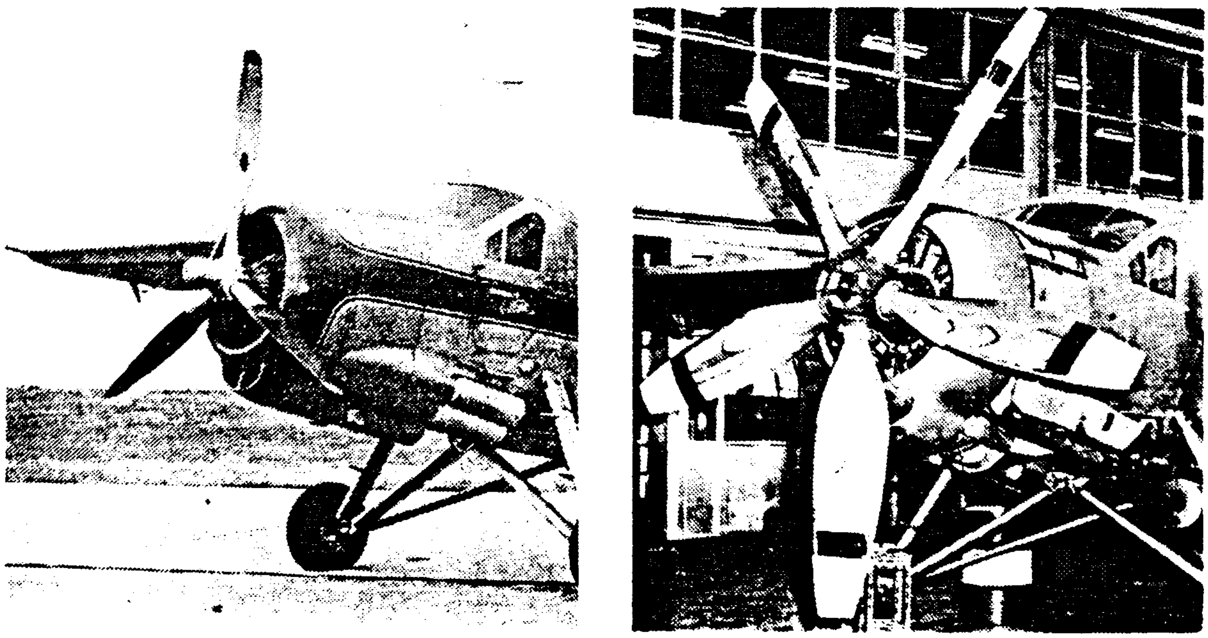


FIGURE 2.14 Comparison of Standard and Modified Otter (Ref. 2.4)

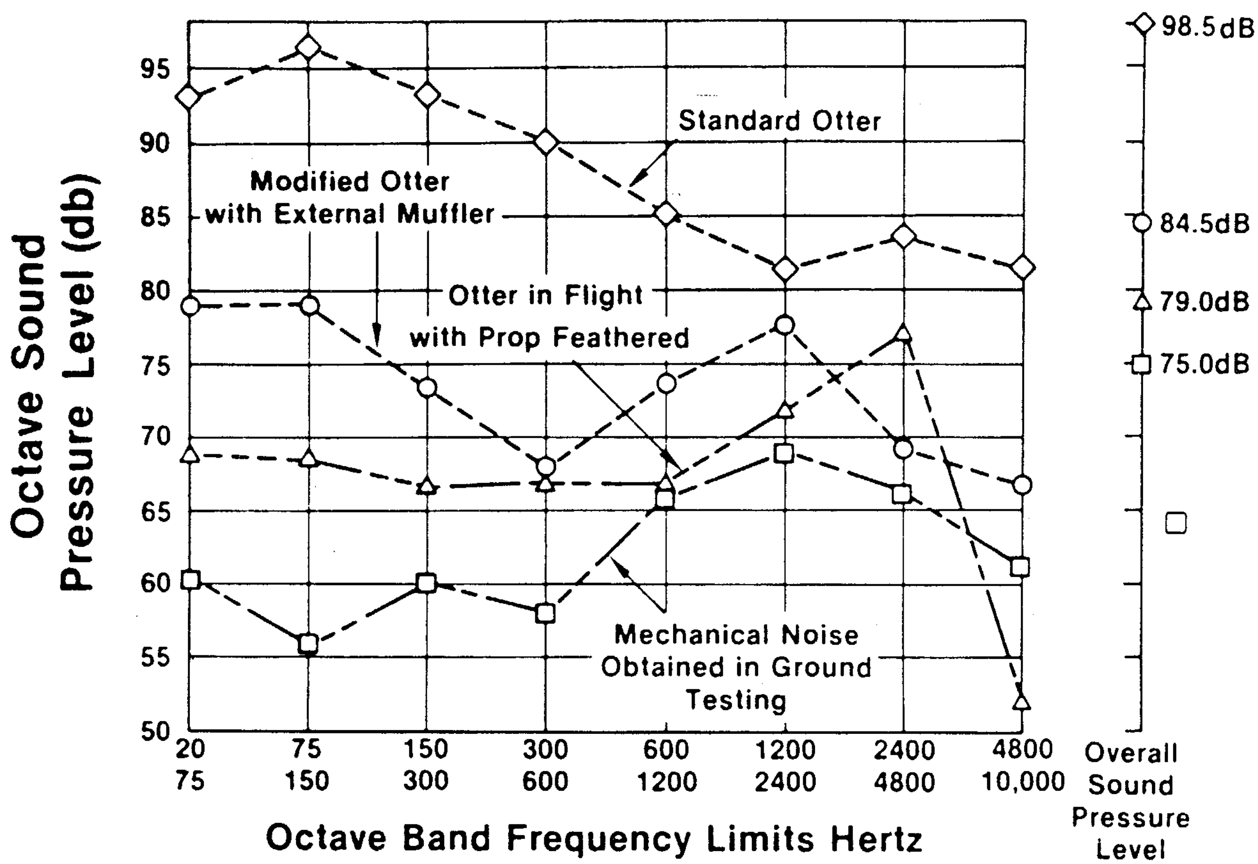


FIGURE 2.15 Comparison of Standard and Modified Otter Noise (120 mph, cruise power, 200 ft distance) (Ref. 2.4)

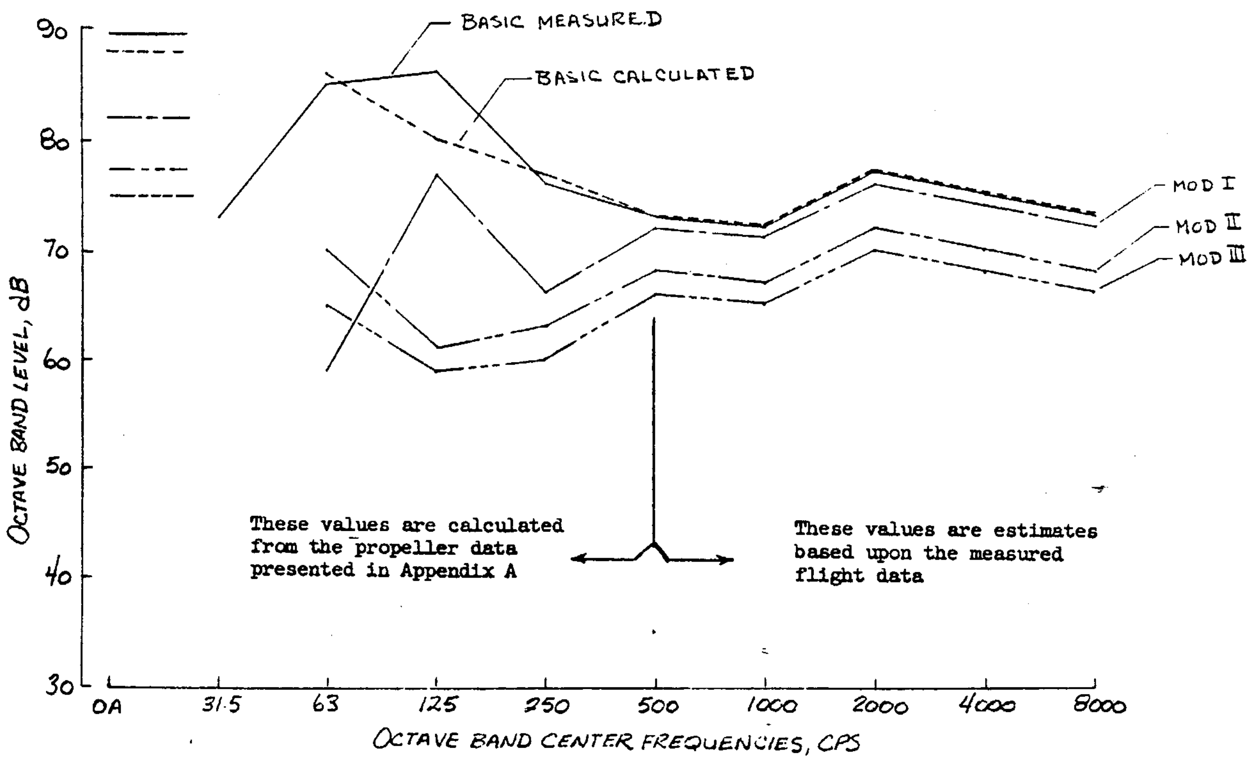


FIGURE 2.16 Estimated Octave Band Spectra for Various Versions of the OV-1 (Distance 300 ft) (Ref. 2.13)

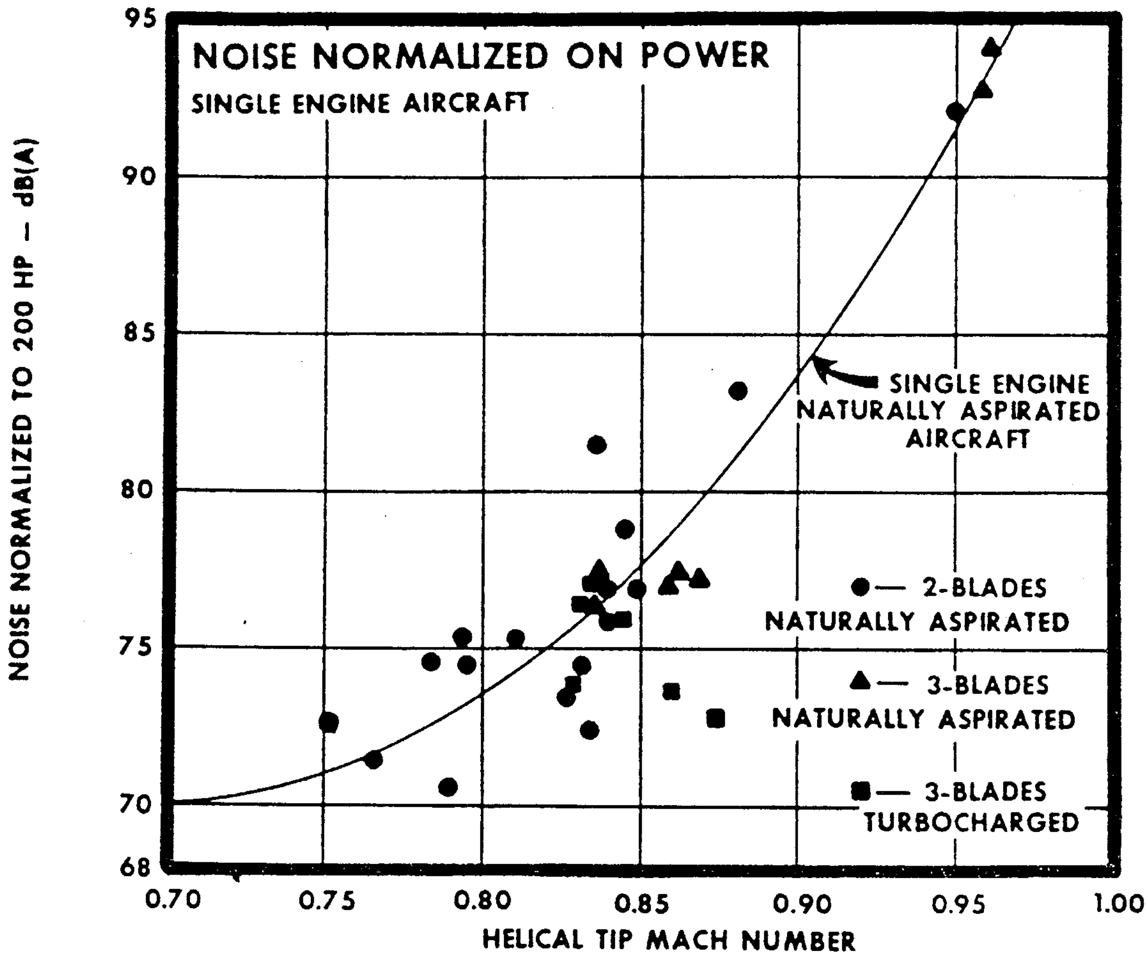


FIGURE 2.17 Flyover Noise Data for Single Engine Aircraft with the Observed Noise Levels Normalized to 200 hp. (Ref. 2.14)

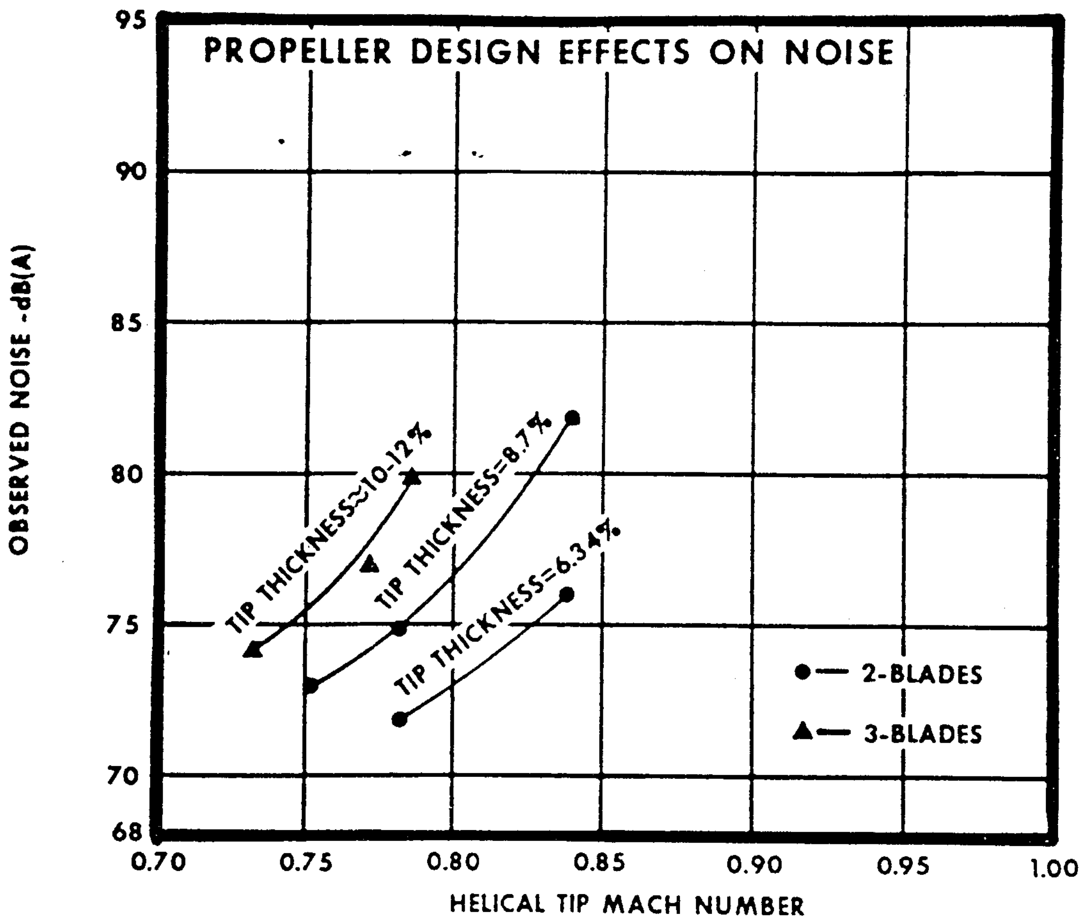


FIGURE 2.18 Influence of Propeller Airfoil Properties on Observed Noise (Ref. 2.14)

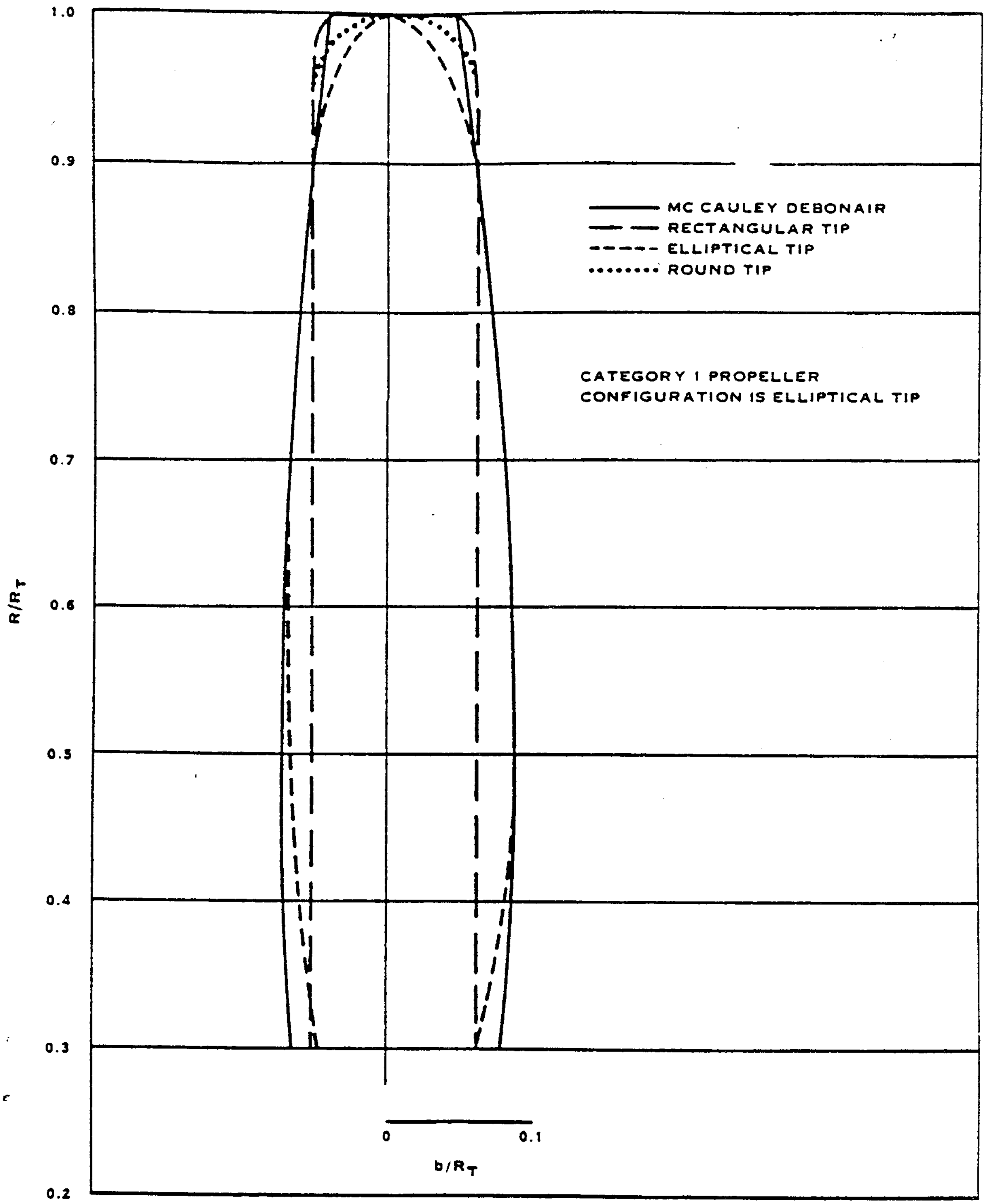


FIGURE 2.19 Single Engine Debonair Propeller Blade Planforms (Ref. 2.18)

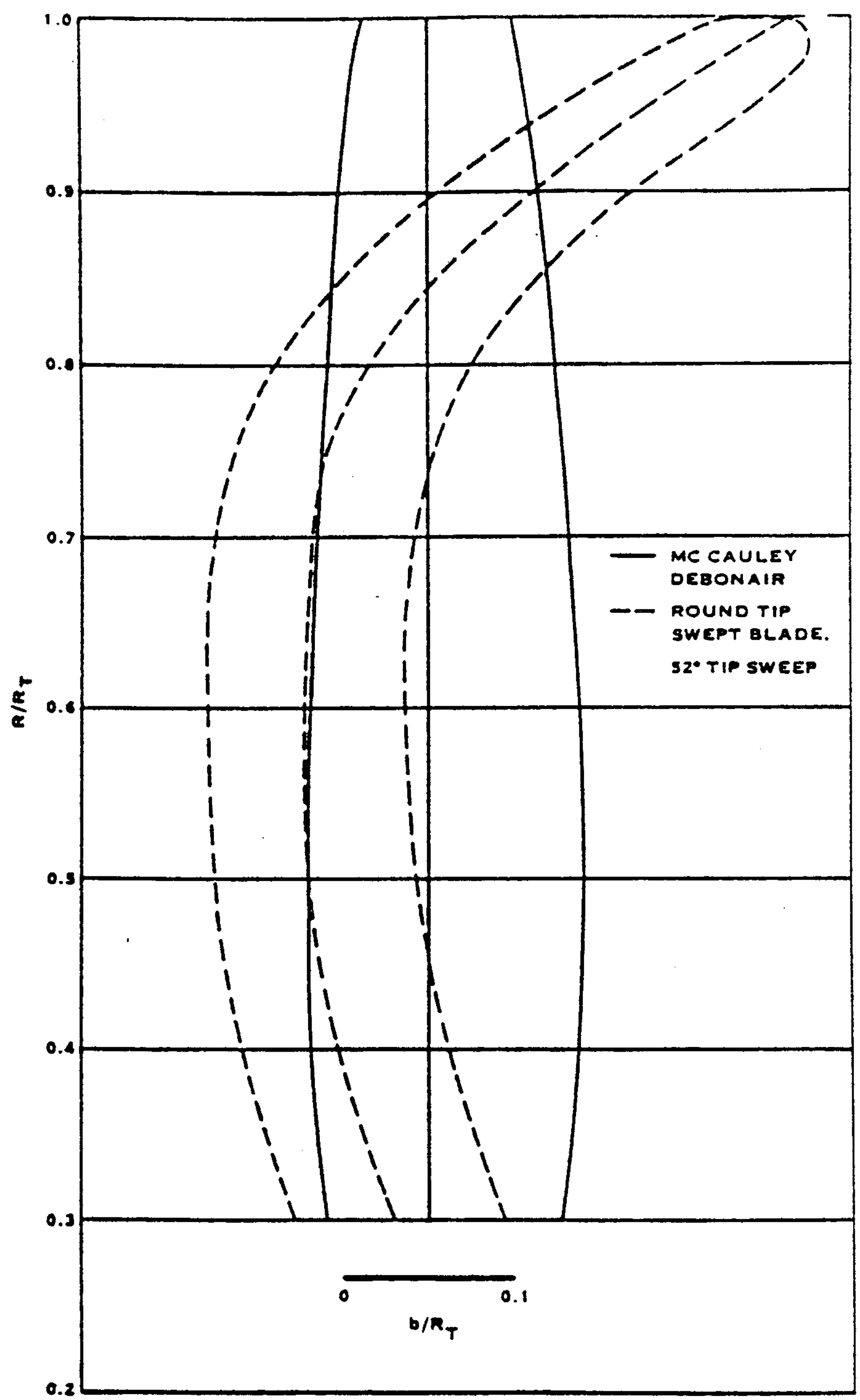


FIGURE 2.20 Single Engine Debonair Propeller Blade Planforms (Ref. 2.18)

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
DIAMETER (FT)	7	7	7	7	7	7	7	7	7	7	6.5	6.5	7	6.25	6.5	6.25	6.25	6.25	6.25
NO. BLADES	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	3	3	3	3
AIRFOIL	RAF-6	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	R	R	N	R	N	N	N	N	N	N	N	N	N
TIP SHAPE	N	RO	E	N	RE	RO	RE	RO	E	E	E	N	RO	E	E	N	E	RO	RO
TIP THICKNESS	TK	TK	TK	TH	TH	TH	TH	TH	TH	TH	TK	TH	TH	TK	TH	TH	TH	TK	TH
TIP SWEEP	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	52°	0°	0°	0°	0°	52°	52°

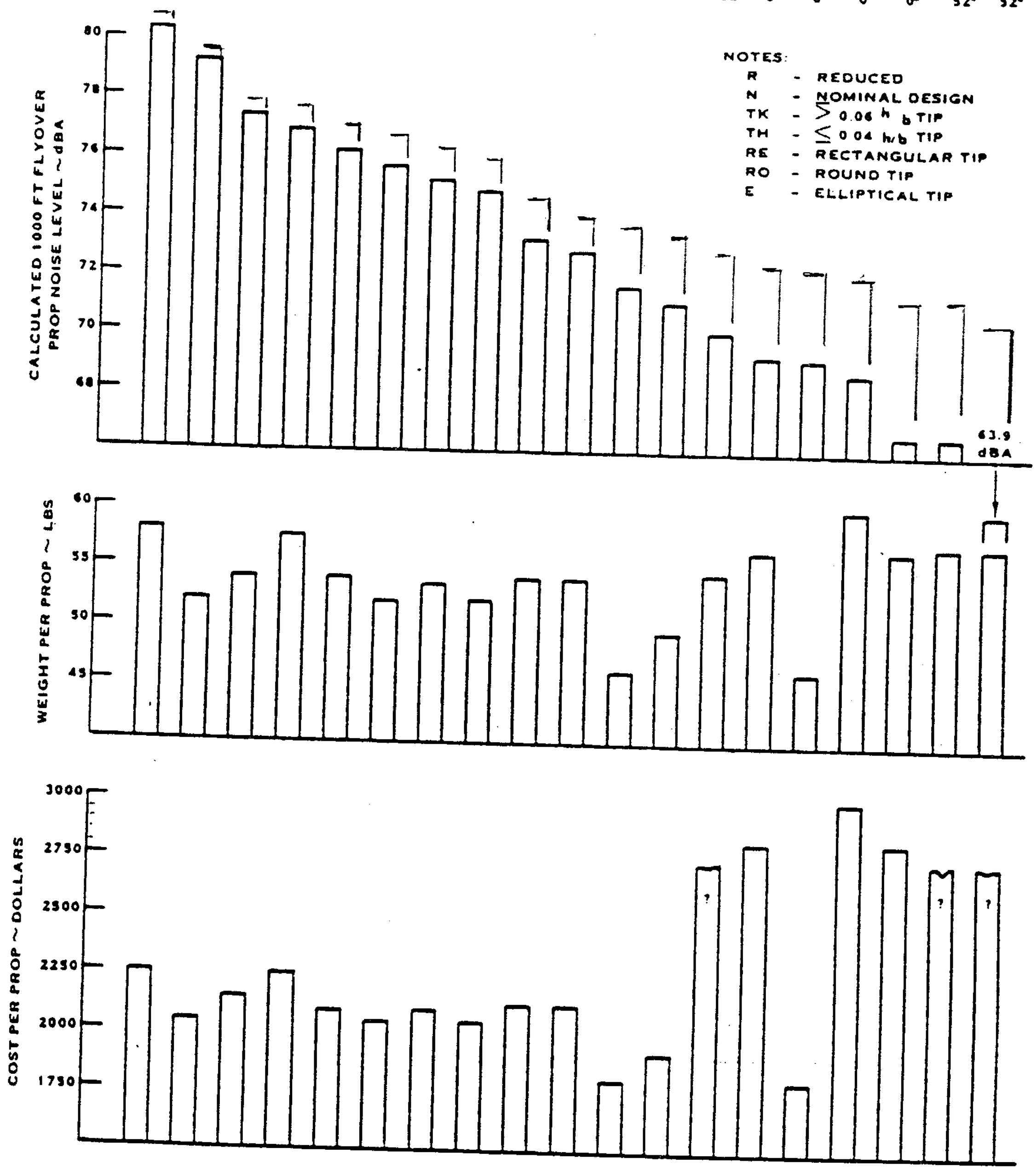


FIGURE 2.21 Debonair Study Summary (Ref. 2.18)

CONFIGURATION	1	2	3	4	5	6	7	8	9	10	11
DIAMETER (FT)	6.33	6.2	6.1	5.85	6.10	5.85	5.75	5.75	5.85	5.70	5.65
NO. BLADES	2	2	2	3	2	3	3	3	3	4	4
AIRFOILS	CL	16	16	16	16	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N	N	R	N	N
TIP SHAPE	N	N	N	E	E	N	N	E	E	N	E
TIP THICKNESS	TK	TH	TH	TK	TH	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	95.3	80	95.7	89.6	89.8	95.7	80	89.8	89.8	80	80

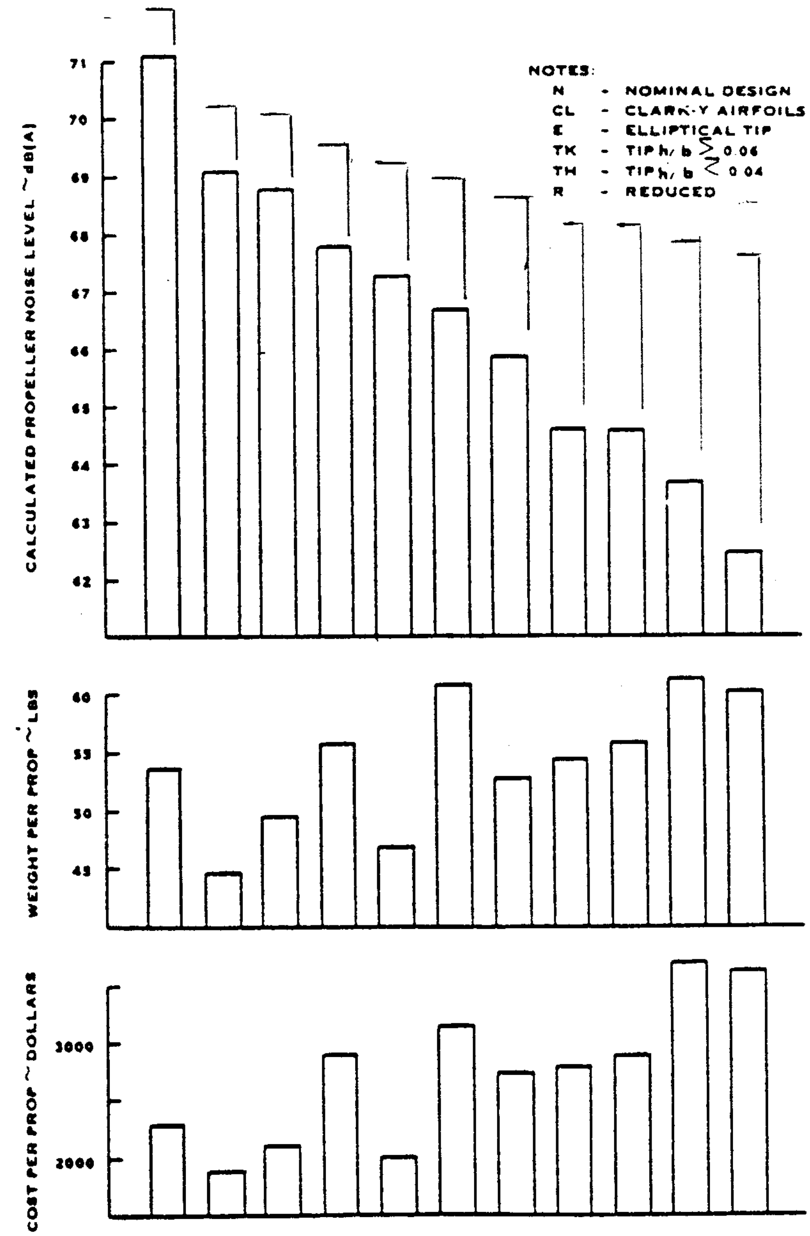


FIGURE 2.22 Beech 76 Duchess Study Summary (Ref. 2.18)

CONFIGURATION	1	2	3	4	5	6	7
DIAMETER (FT)	8.5	8.5	8.35	8.5	8.1	8.1	8.0
NO. BLADES	3	3	3	3	4	4	5
AIRFOIL	CL	16	16	16	16	16	16
TIP LOADING	N	N	N	N	N	N	N
TIP SHAPE	N	E	E	OV10	N	E	N
TIP THICKNESS	TO	TH	TH	TH	TH	TH	TH
ACTIVITY FACTOR	114.6	89.8	89.8	90	80	80	80

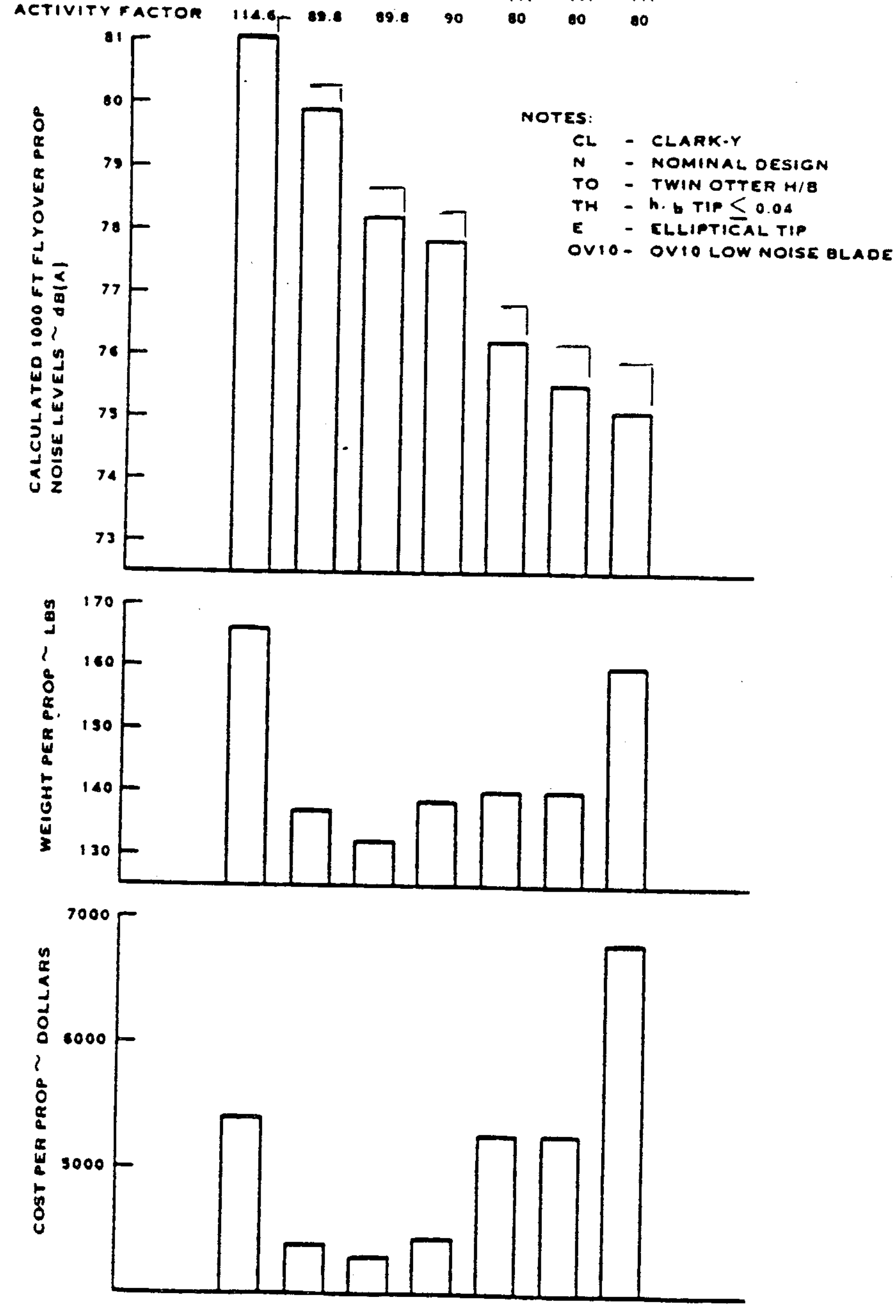


FIGURE 2.23 Heavy Twin Engine, Twin Otter, Study Summary (Ref. 2.18)

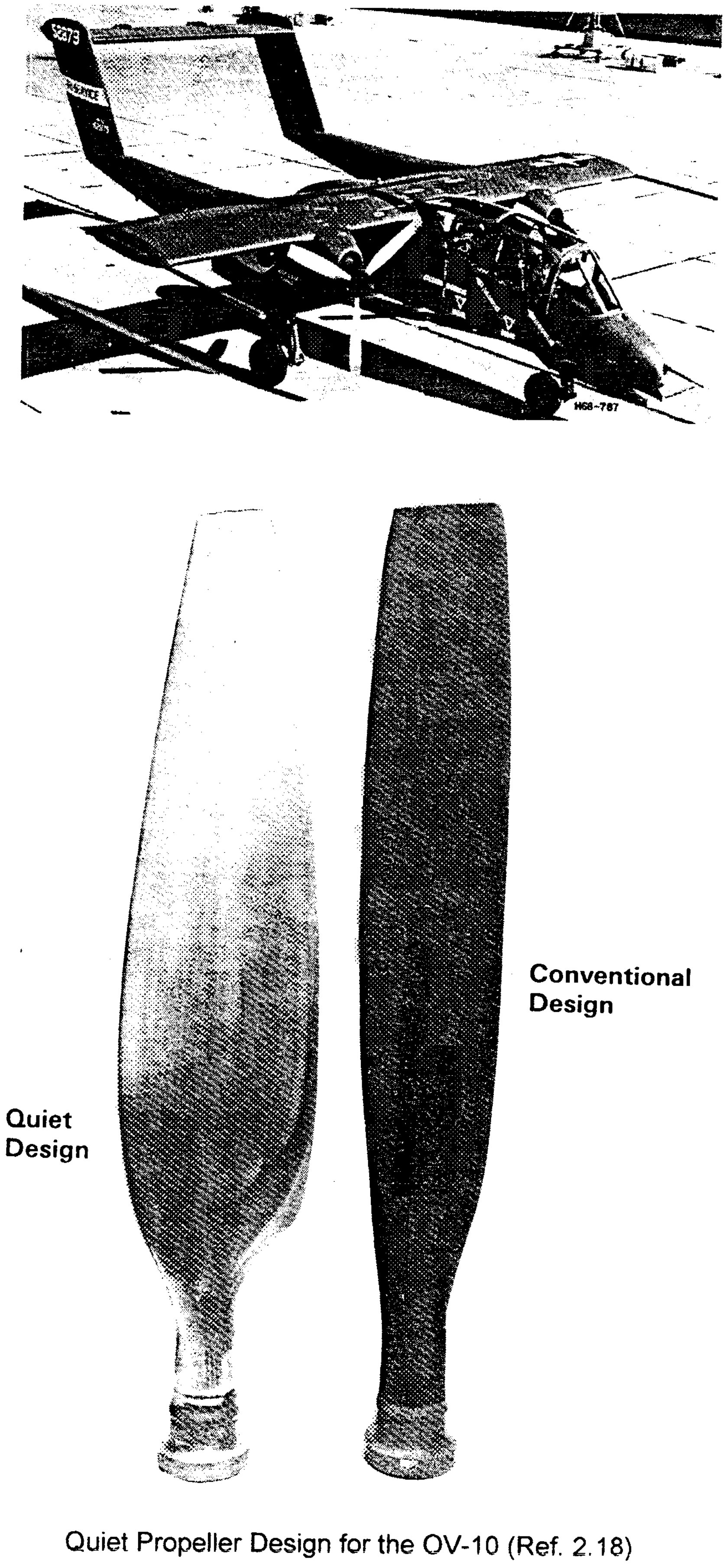


FIGURE 2.24 Quiet Propeller Design for the OV-10 (Ref. 2.18)

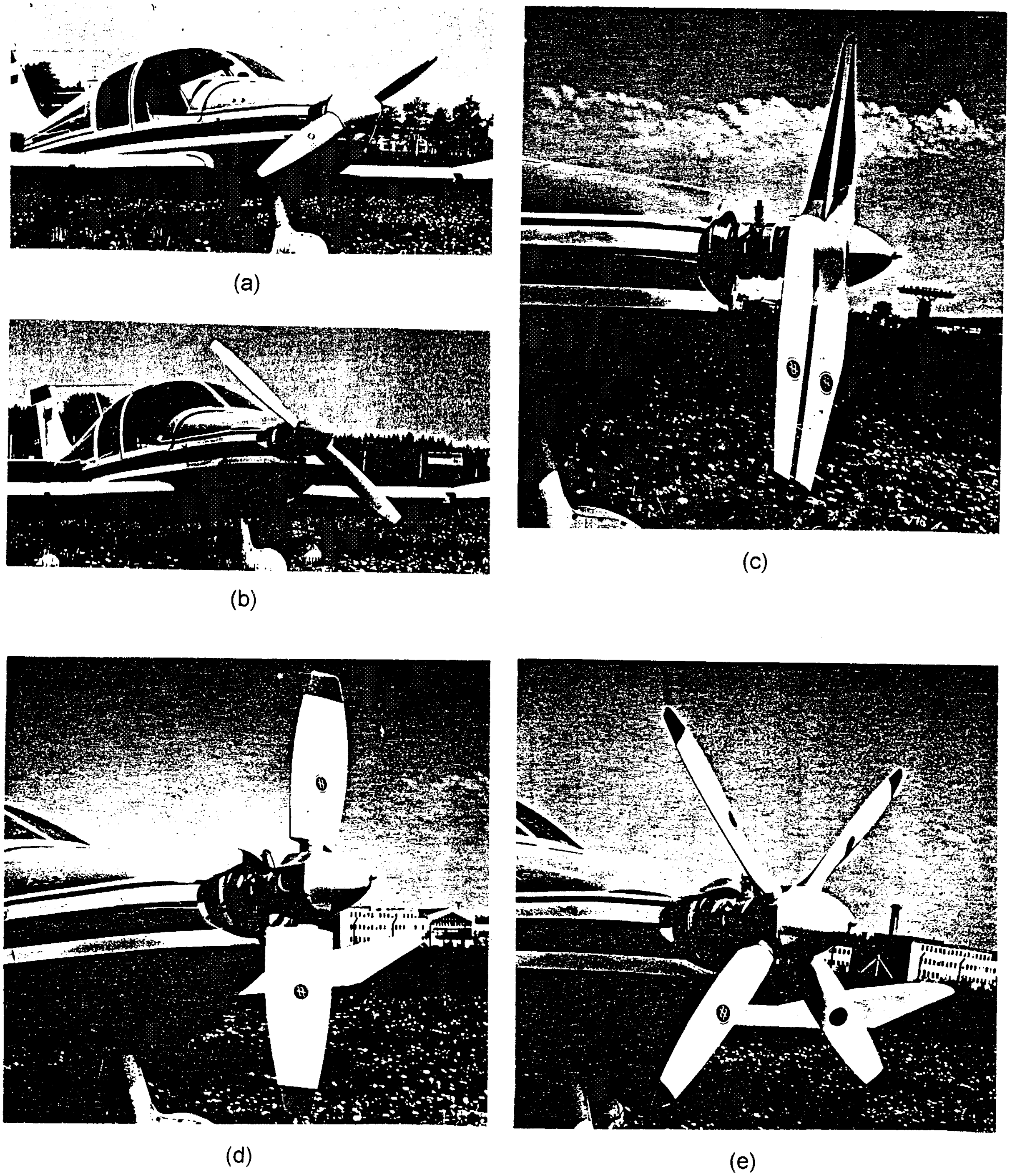


FIGURE 2 25 Propeller Test Configurations, (a) Original Propeller H027HM-180-138, (b) Original Propeller Se76EM8S-5-0-58, (c) Bi-Propeller,HOB 27-165 116 152 (bauahnlich HOB27-165 103 137), (d) Breitblatt-Propeller HO 165BF (22^0) (bauahnlich H0165BF (23^0)), (e) 4-Blatt-Propeller H0165bg (Ref. 2.21)

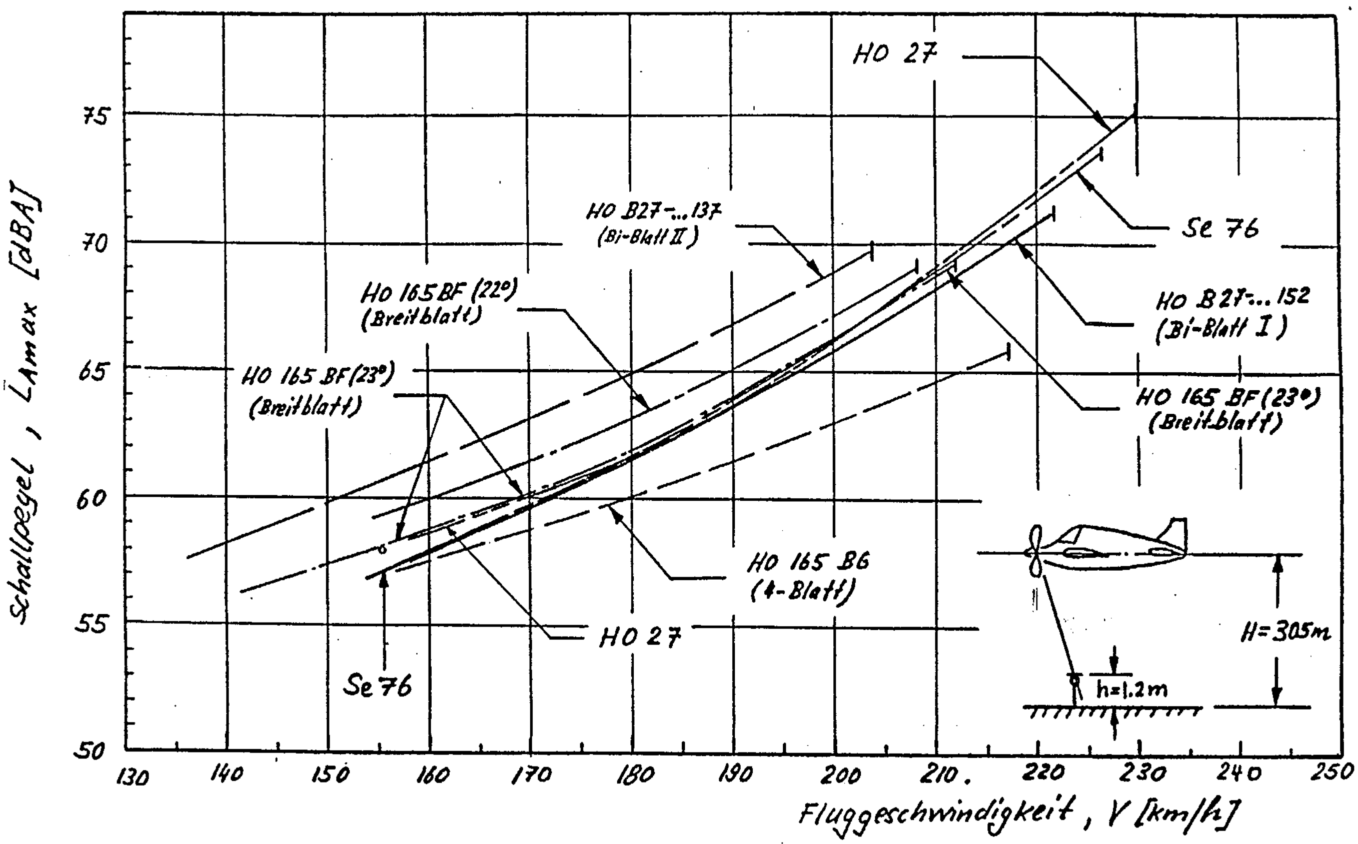


FIGURE 2.26 A-Weighted Noise Levels Versus Level Flight Speed for Various Test Configurations (Ref. 2.21)

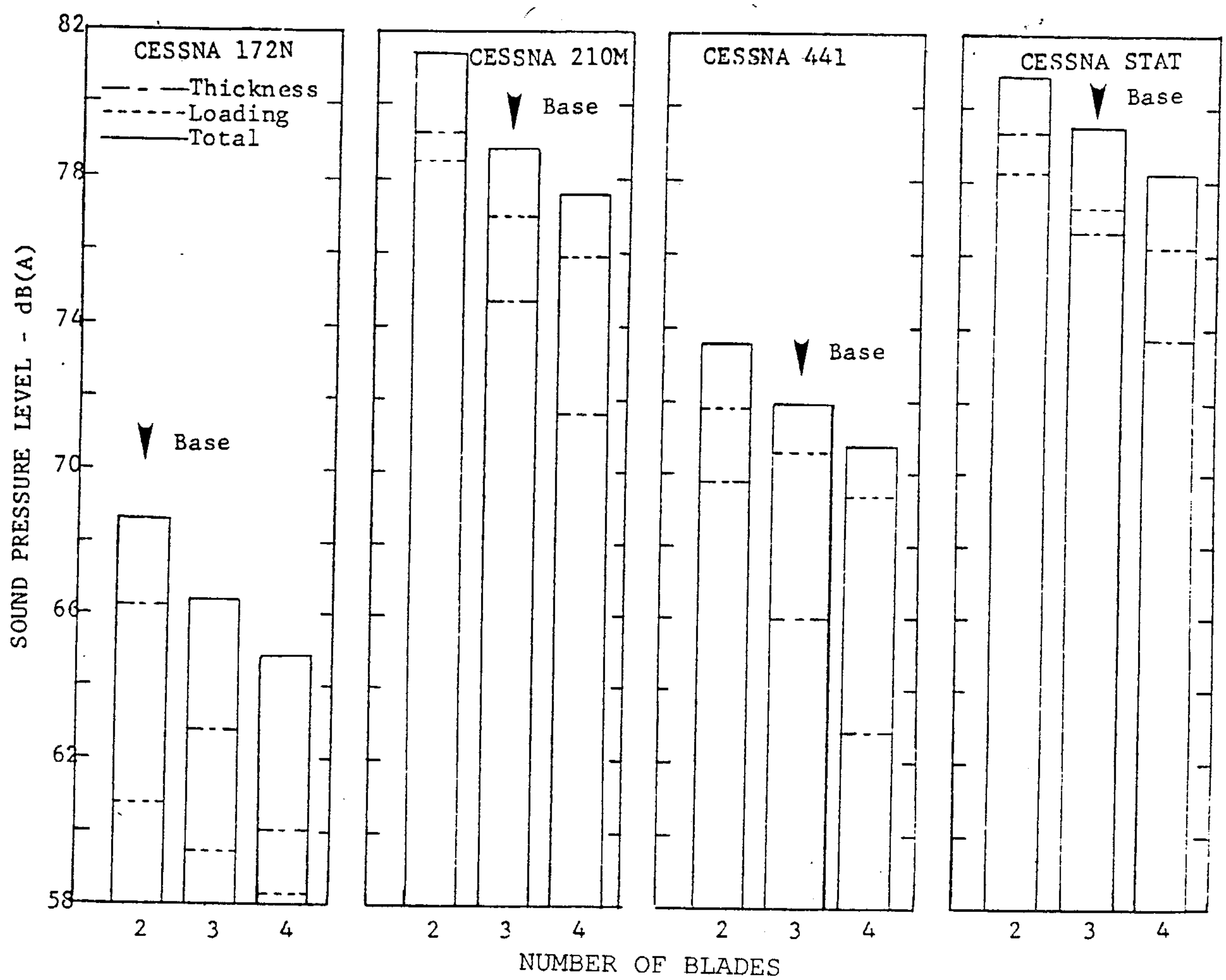


FIGURE 2.27 Effect of Number of Blades on Noise Generated by Various Propellers (Ref. 2.22)

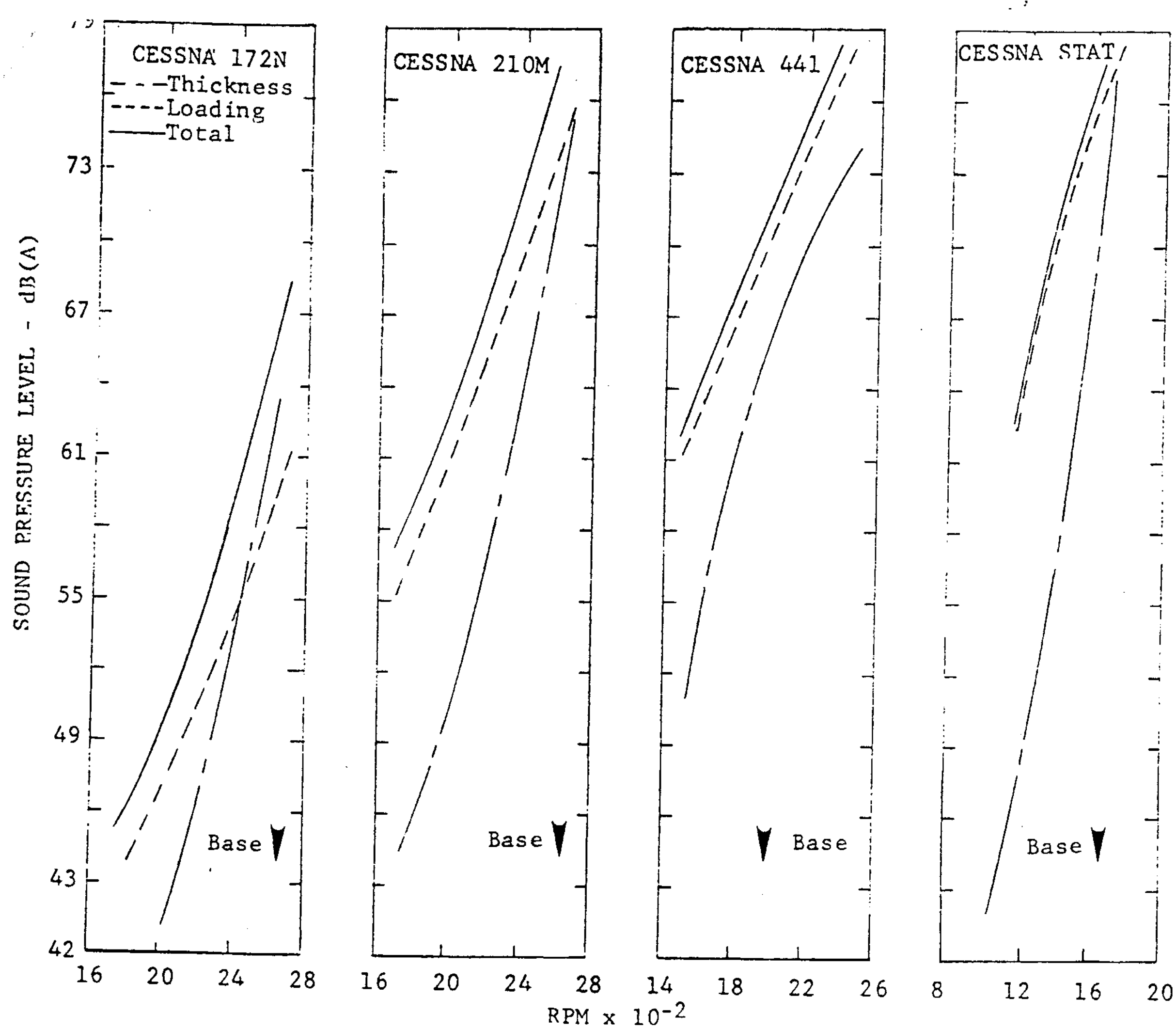


FIGURE 2.28 Effect of Reduced RPM on Noise Generated by Various Propellers (Ref. 2.22)

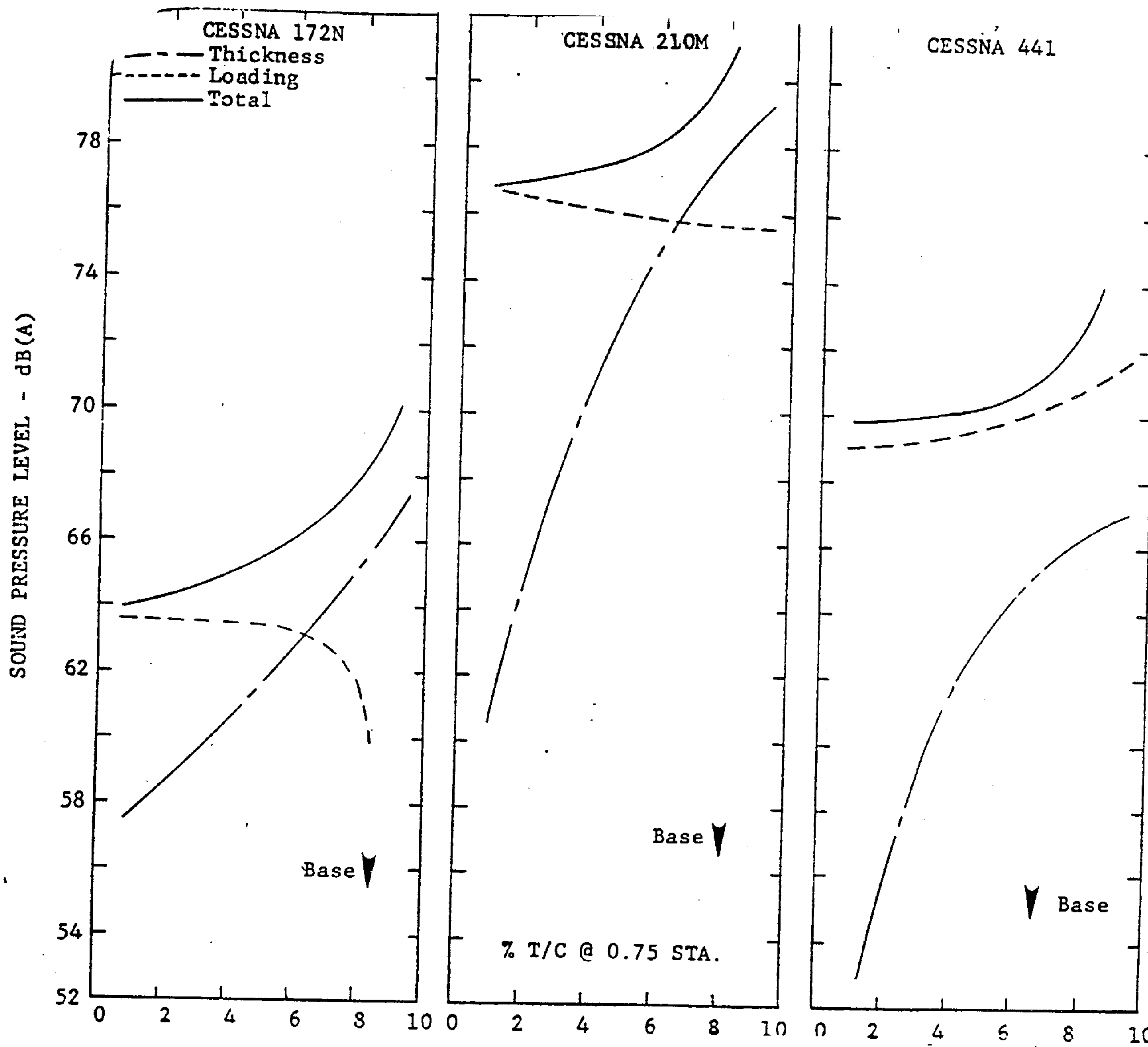


FIGURE 2.29 Effect of Reduced Thickness/Chord Ratio on the Noise Generated by Various Propellers (Ref. 2.22)

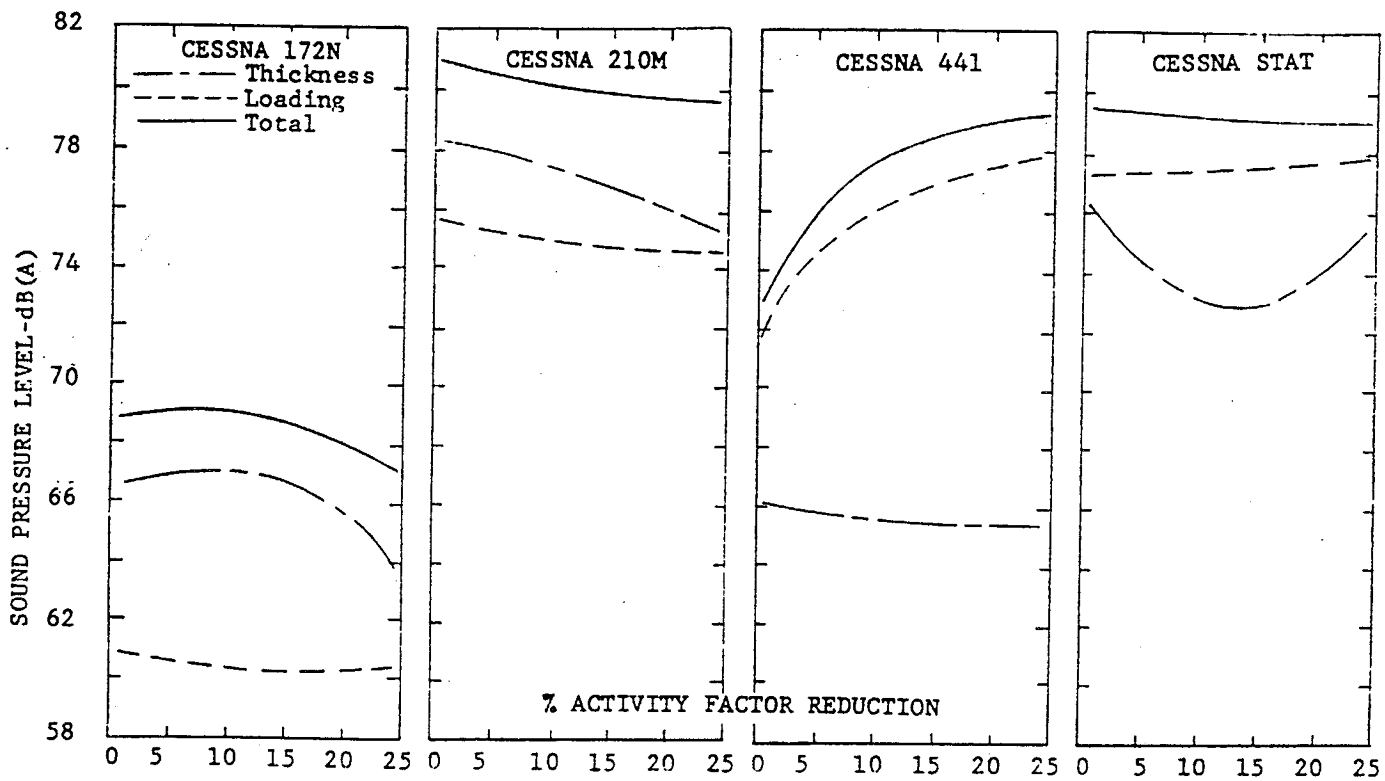


FIGURE 2.30 Effect of Activity Factor Reduction on Noise Generated by Various Propellers (Ref. 2.22)

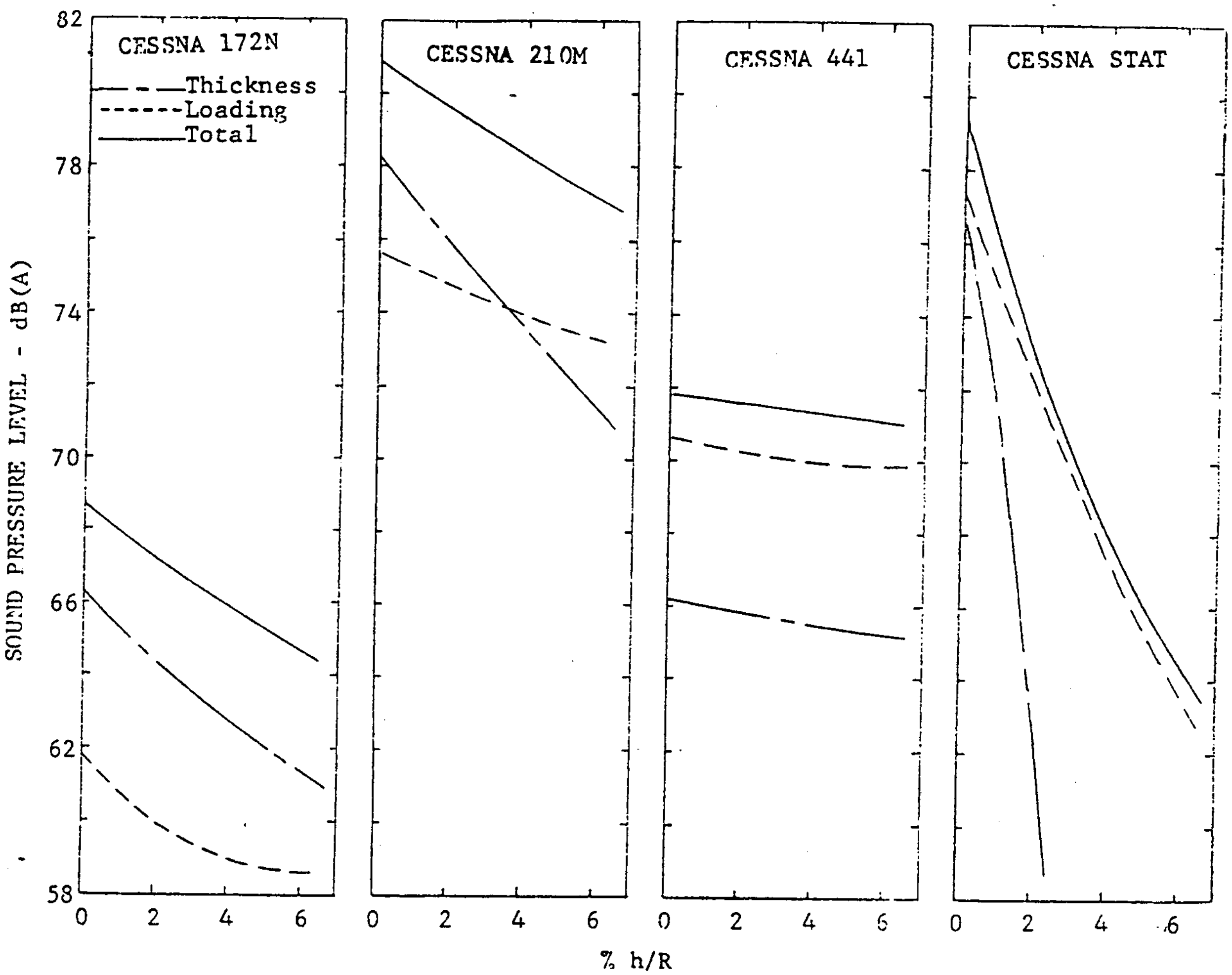


FIGURE 2.31 Effect of Proplets on noise Generated by Various Propellers (Ref. 2.22)

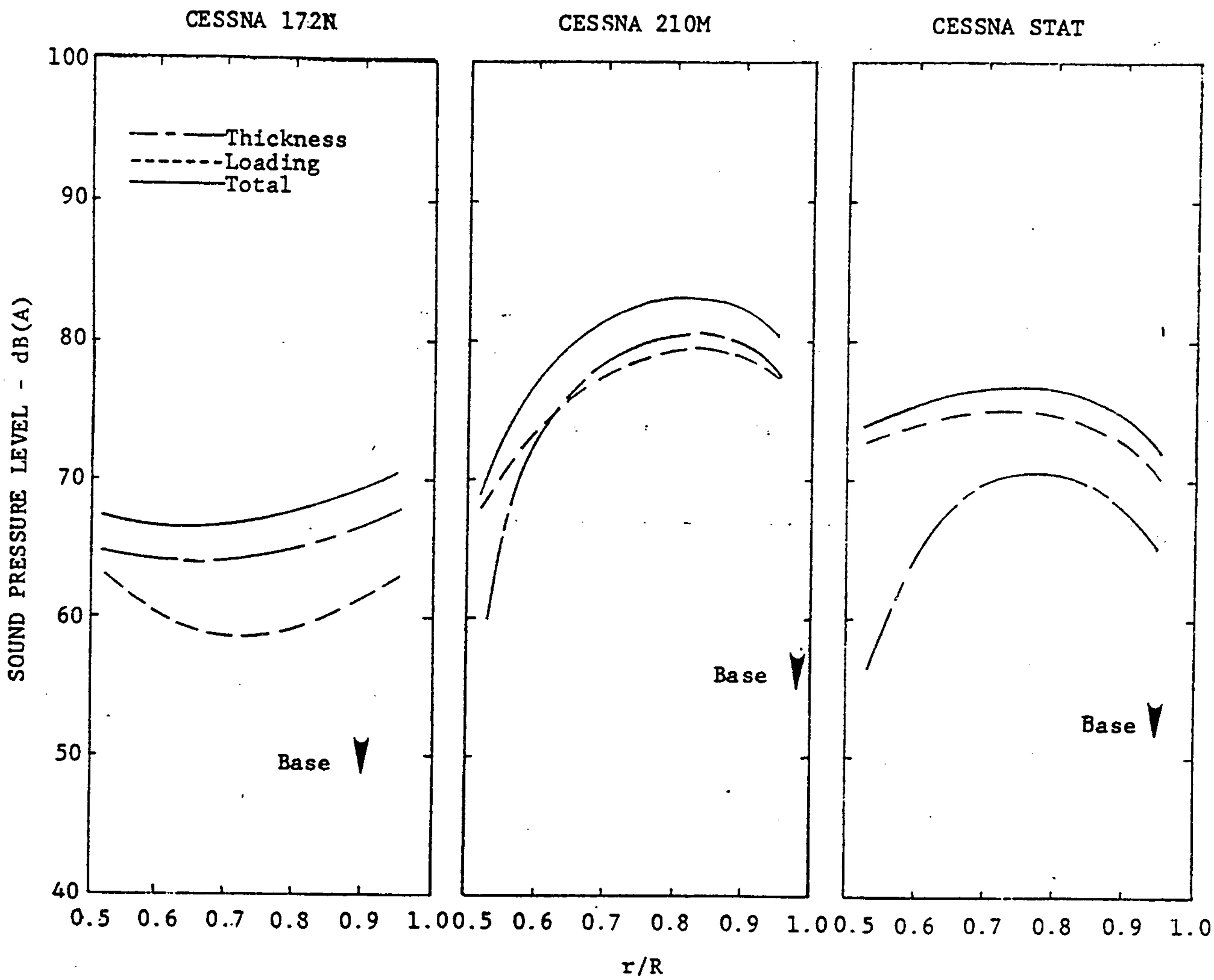


FIGURE 2.32 Effect of Position of Maximum Loading on Noise Generated by Various Propellers (Ref. 2.22)

C-2.

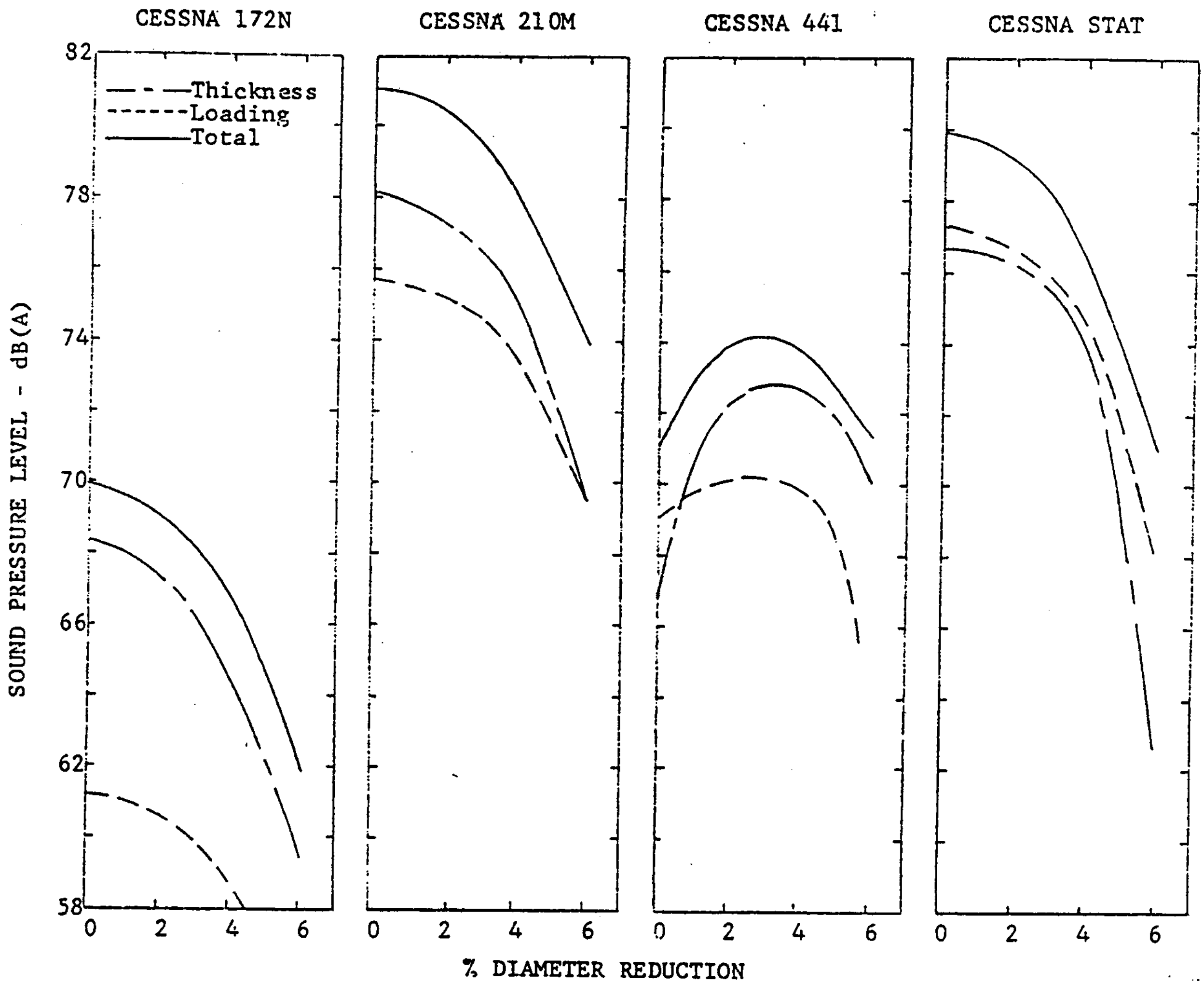


FIGURE 2.33 Effect of Diameter Reduction on Noise Generated by Various Propellers (Ref. 2.22)

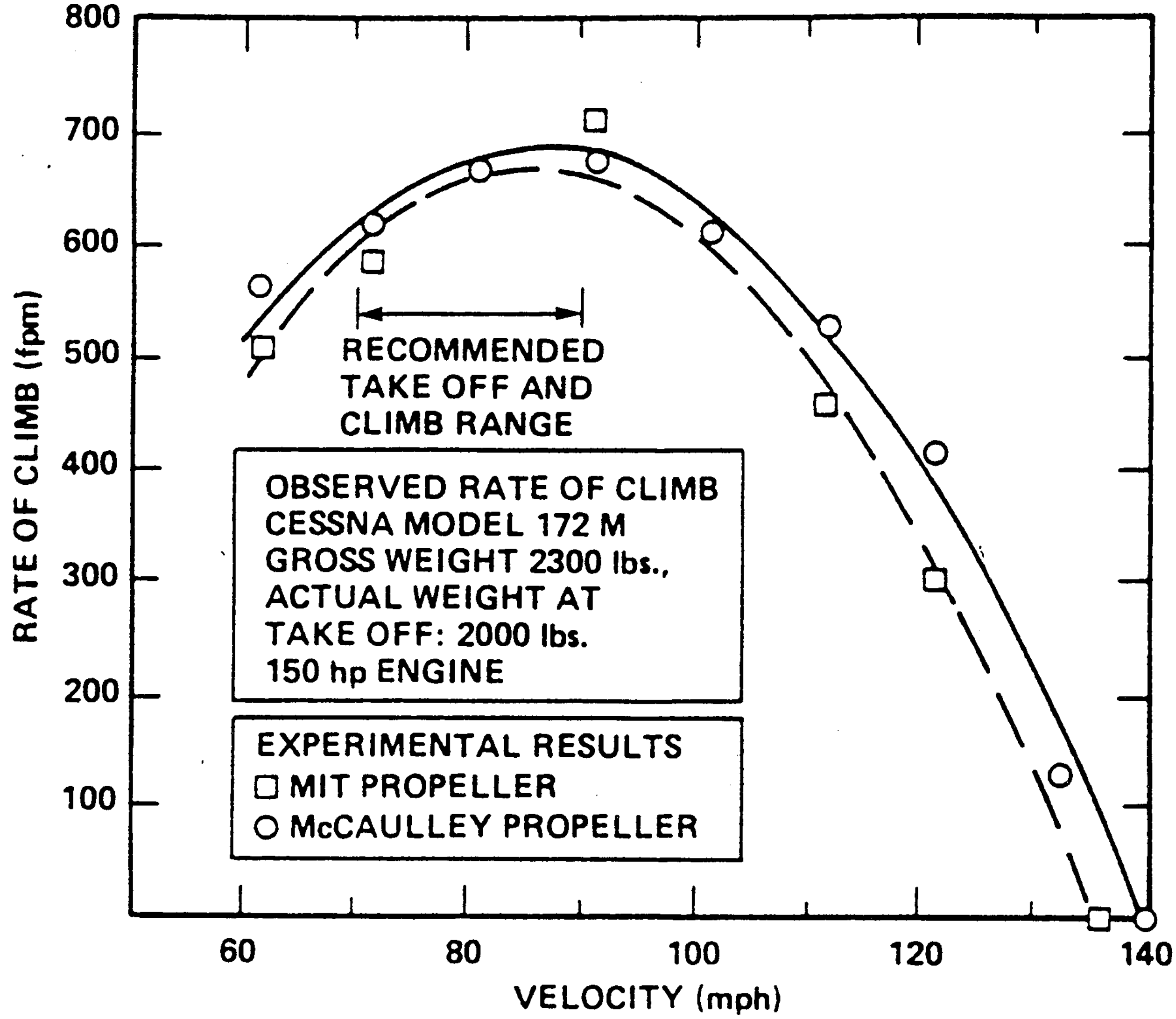


FIGURE 2.34 Measured Performance of the MIT and Production Propeller for Flight Test Conditions (Ref. 2.24)

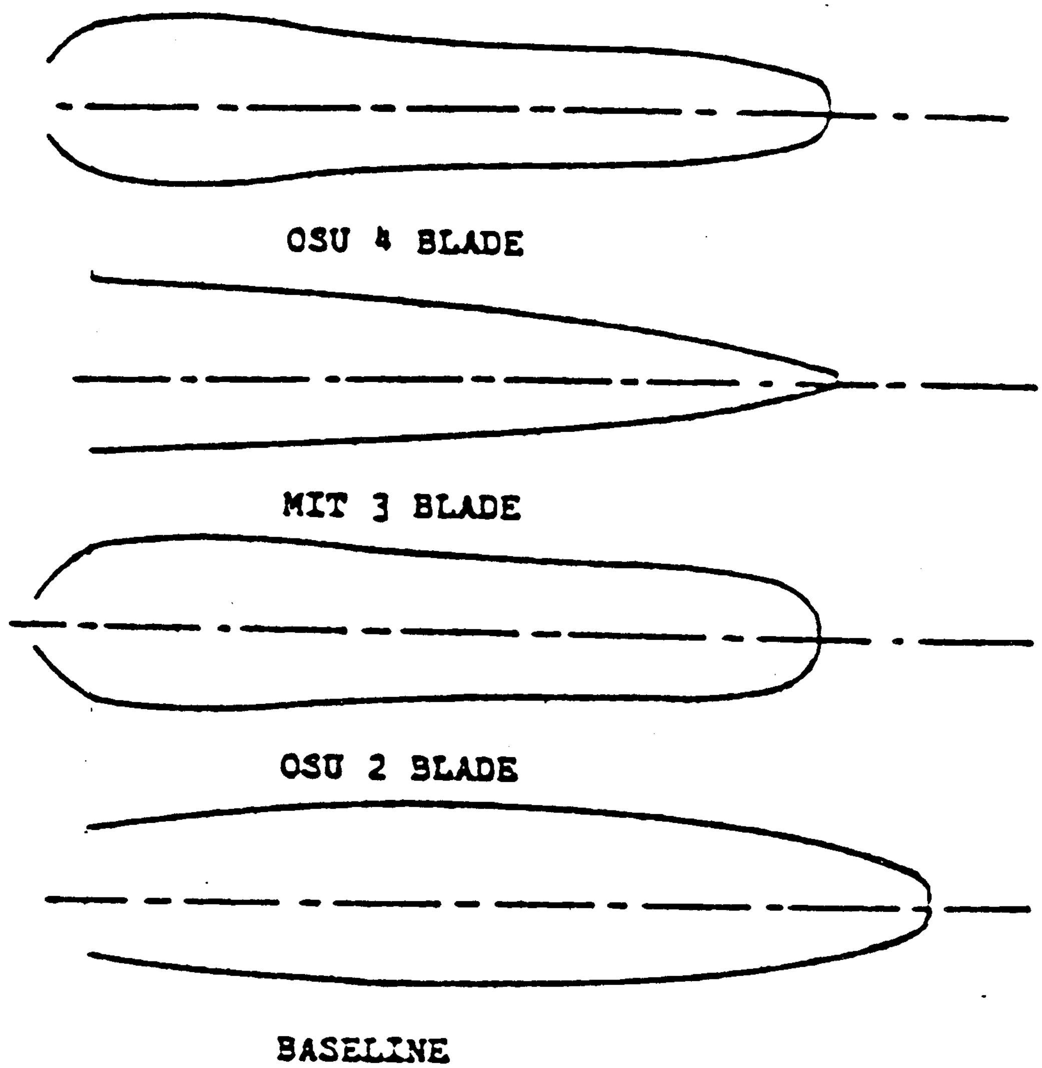


FIGURE 2.35 Blade Planforms for Propellers Tested (Ref. 2.25)

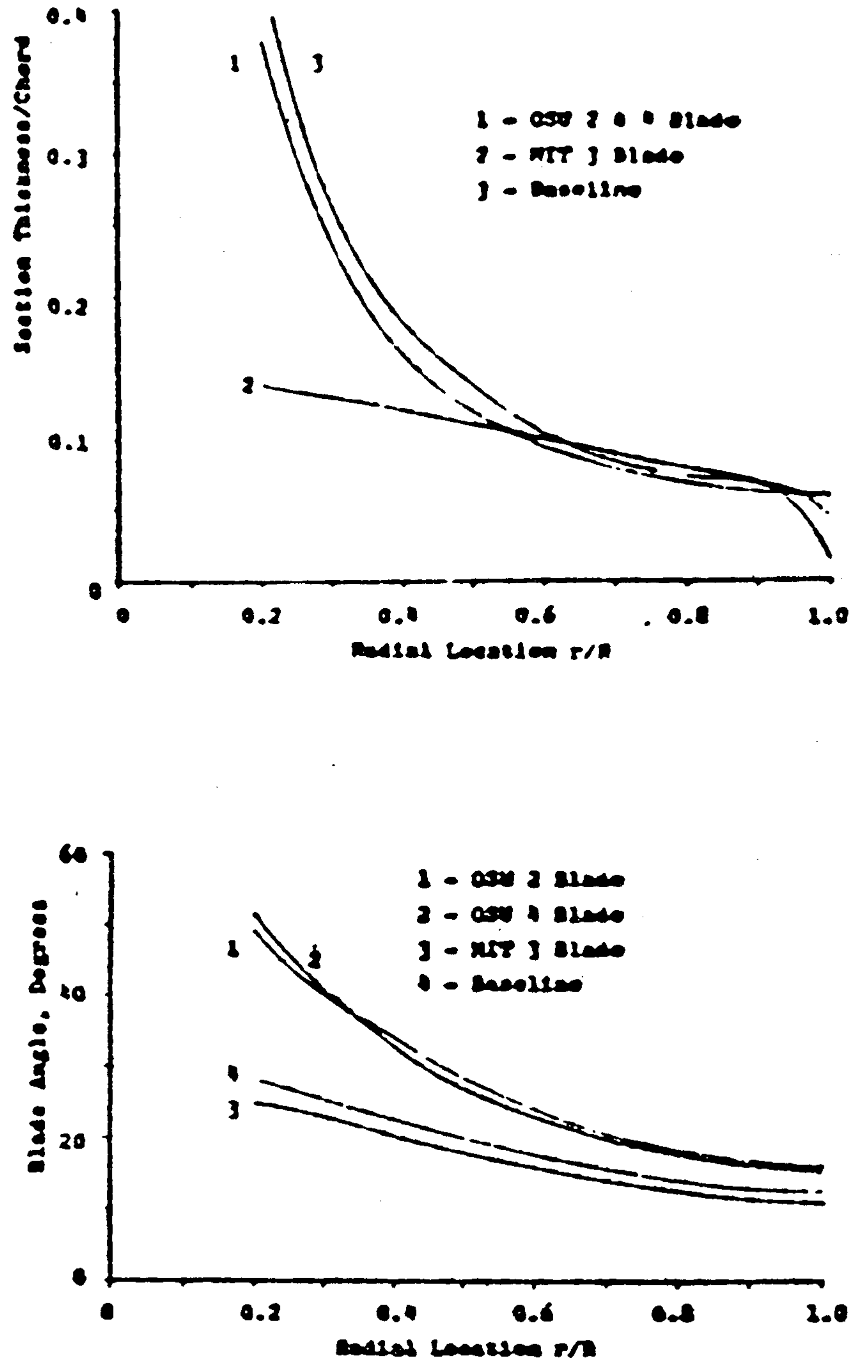


FIGURE 2.36 Thickness Distribution (upper curves) and Twist Distributions (lower curves) for Propellers Tested (Ref. 2.25)

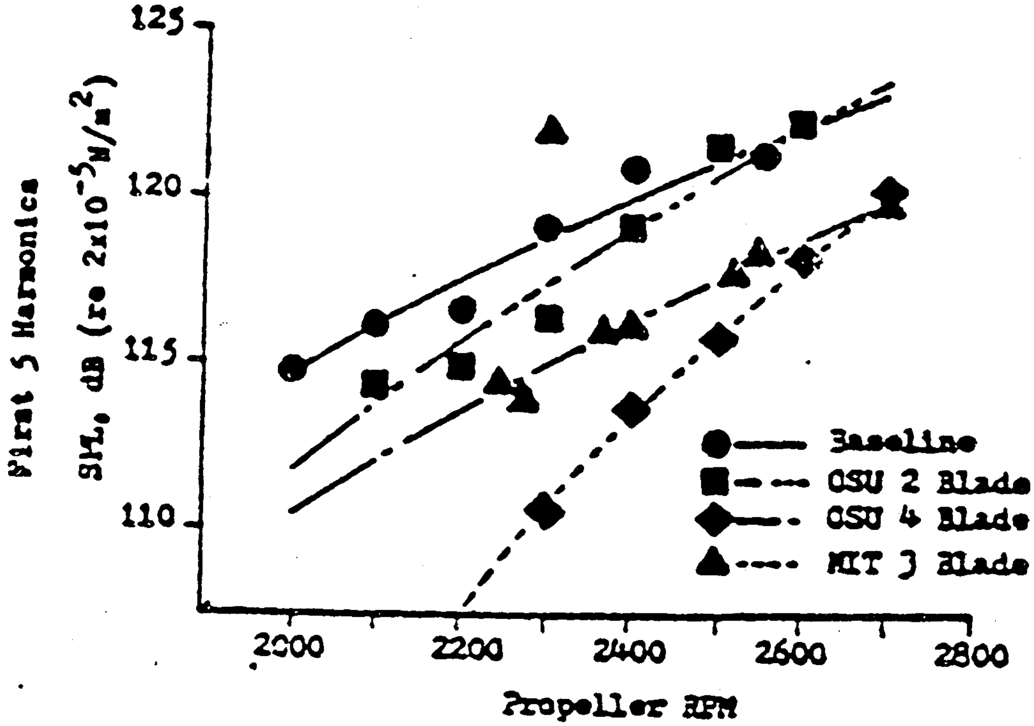
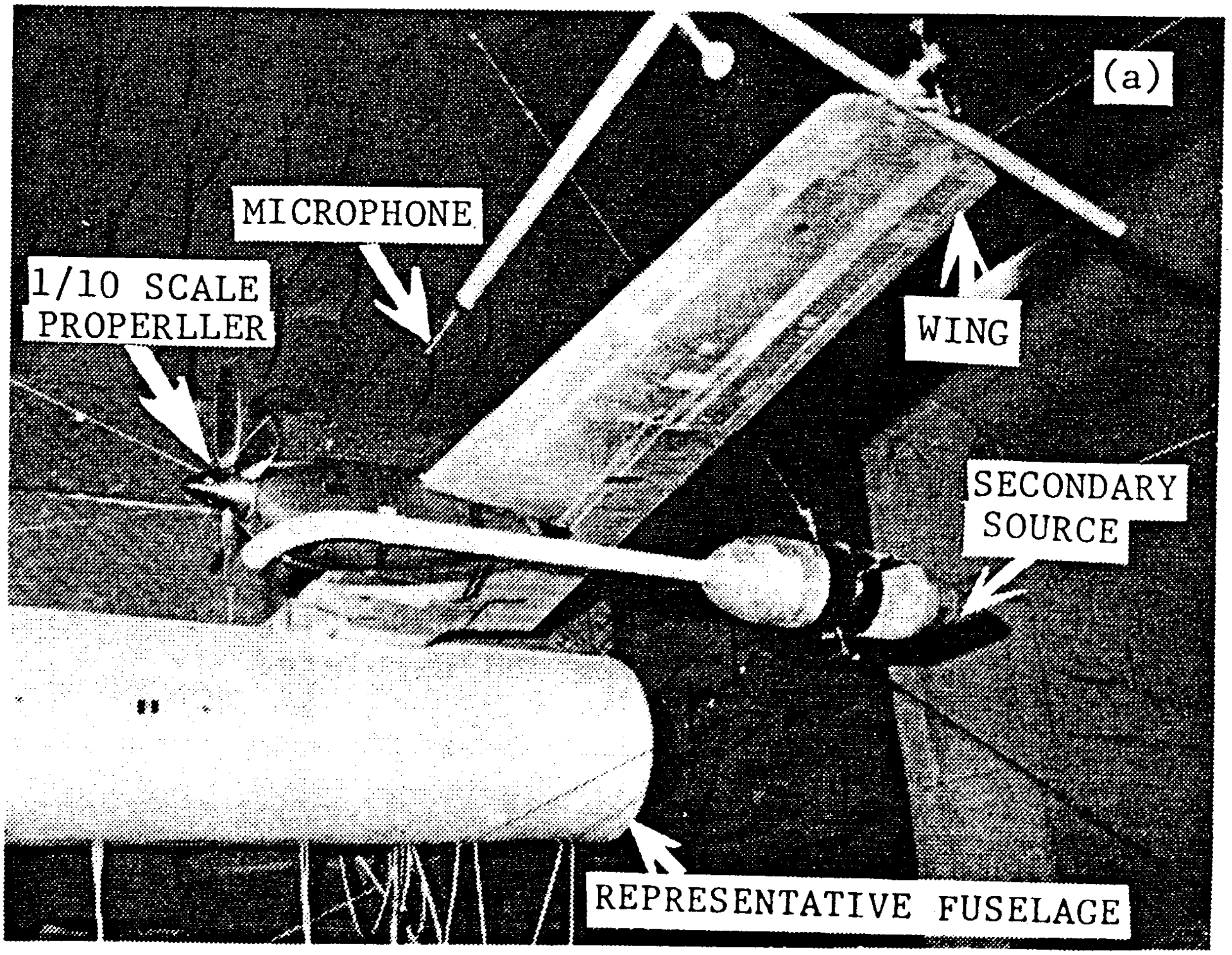


FIGURE 2.37 Noise Level of First Five Harmonics for Propellers Tested (Ref. 2.25)



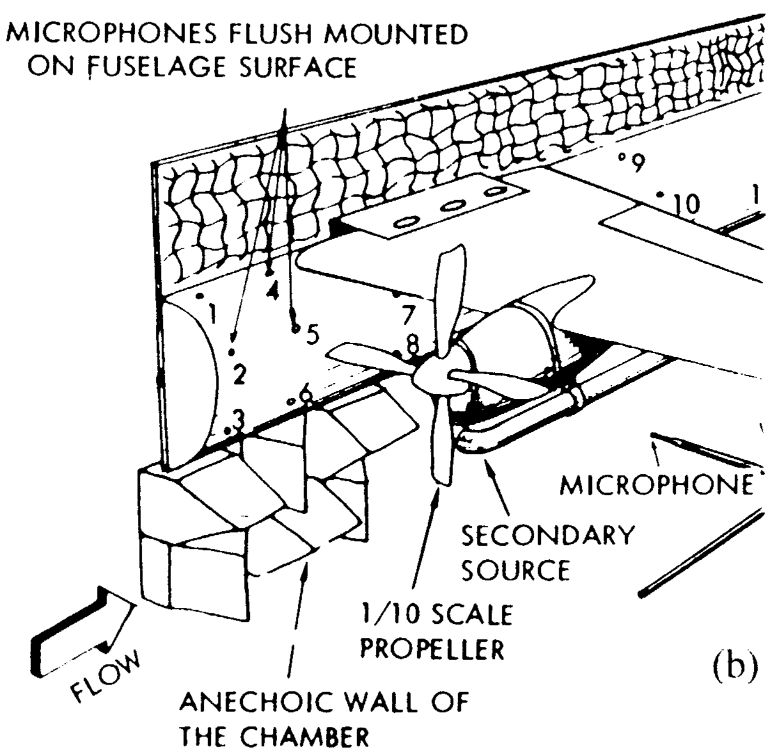


FIGURE 2.38 Arrangement for Active Noise Control Experiment Using a 1/10 Scale C, (a) Photographic View, (b) Schematic View (Rev. 2.26)

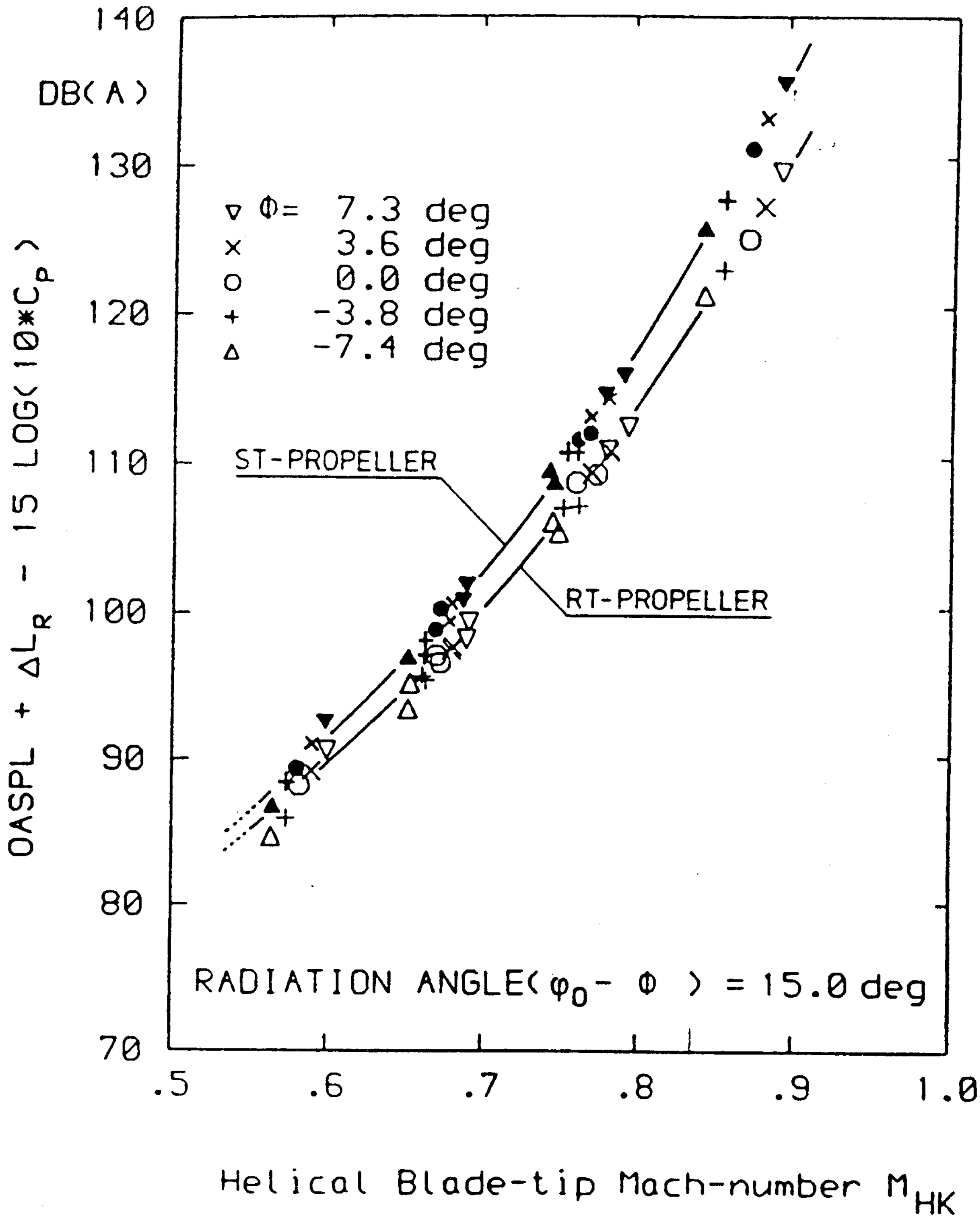


FIGURE 2.39 Normalized A-Weighted Noise Versus Local Helical Tip Mach Number for Various Angles of Attack and for Two Different Propellers (RT - Round Tip and ST - Square Tip) (Ref. 2.27)

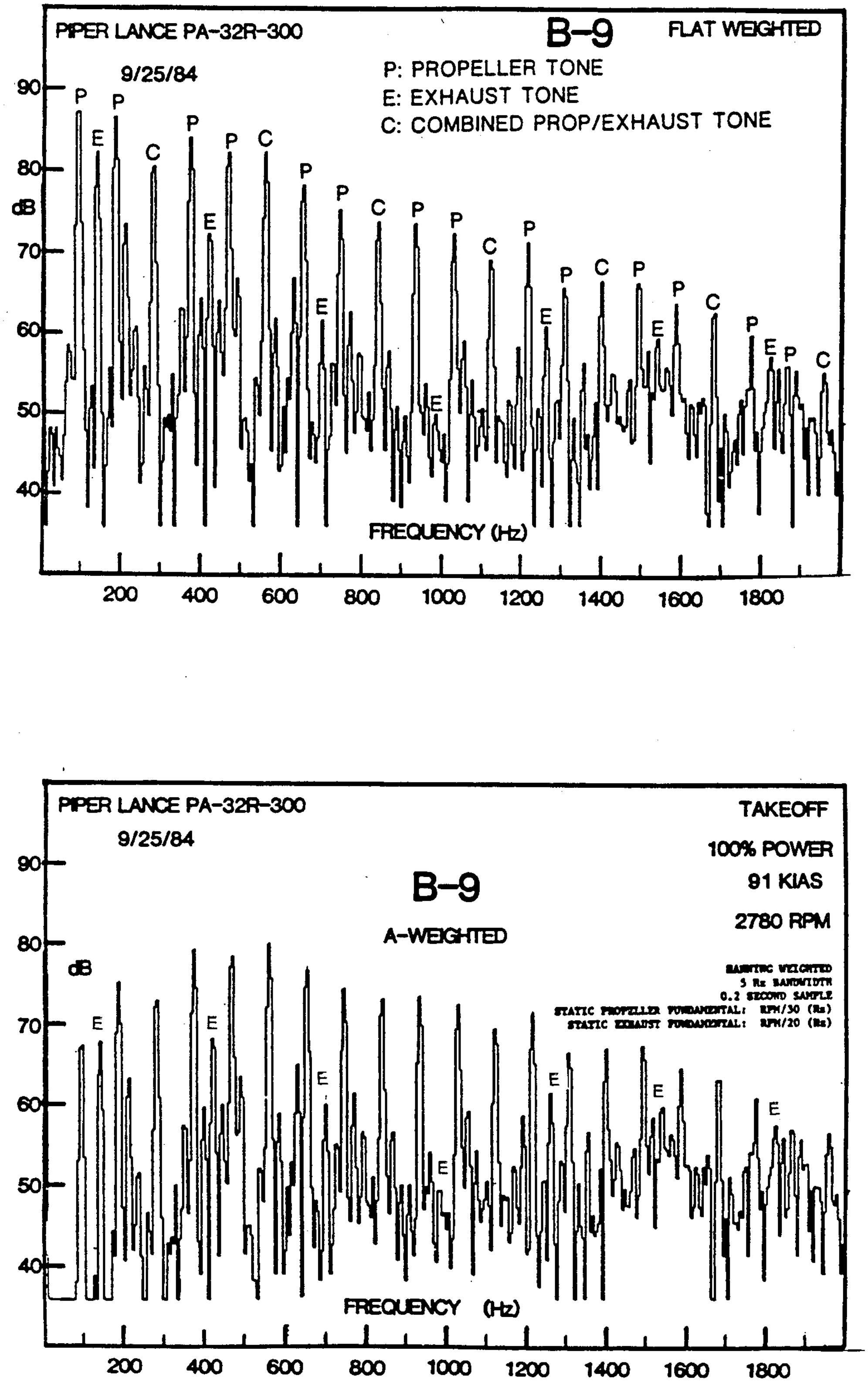


FIGURE 2.40 Flat Weighted (Upper Figure) and A-Weighted (Lower Figure) Narrow Band Noise Spectra for the Piper Lance (Ref. 2.28)

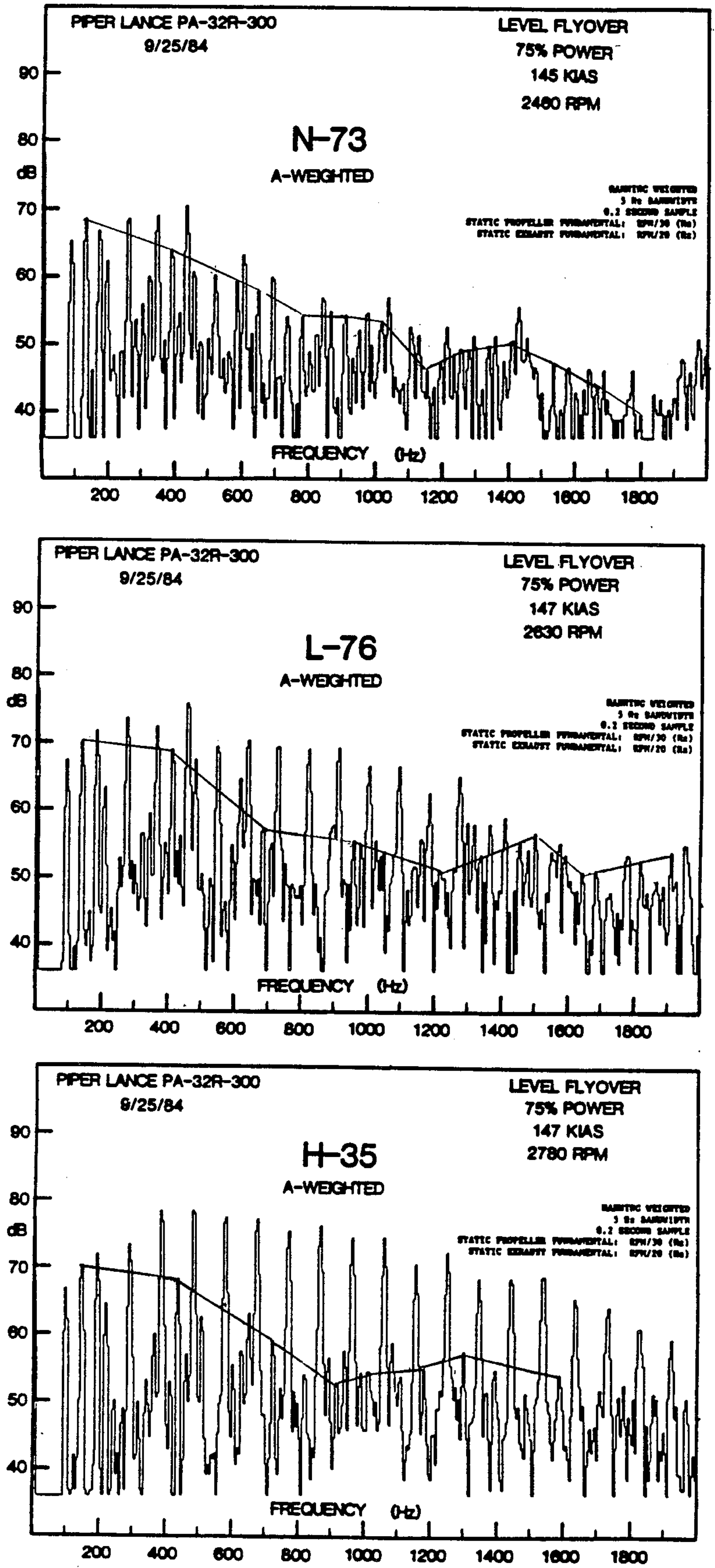


FIGURE 2.41 Effect of Propeller RPM on A-Weighted Noise Spectra for the Piper Lance (Ref. 2.28)

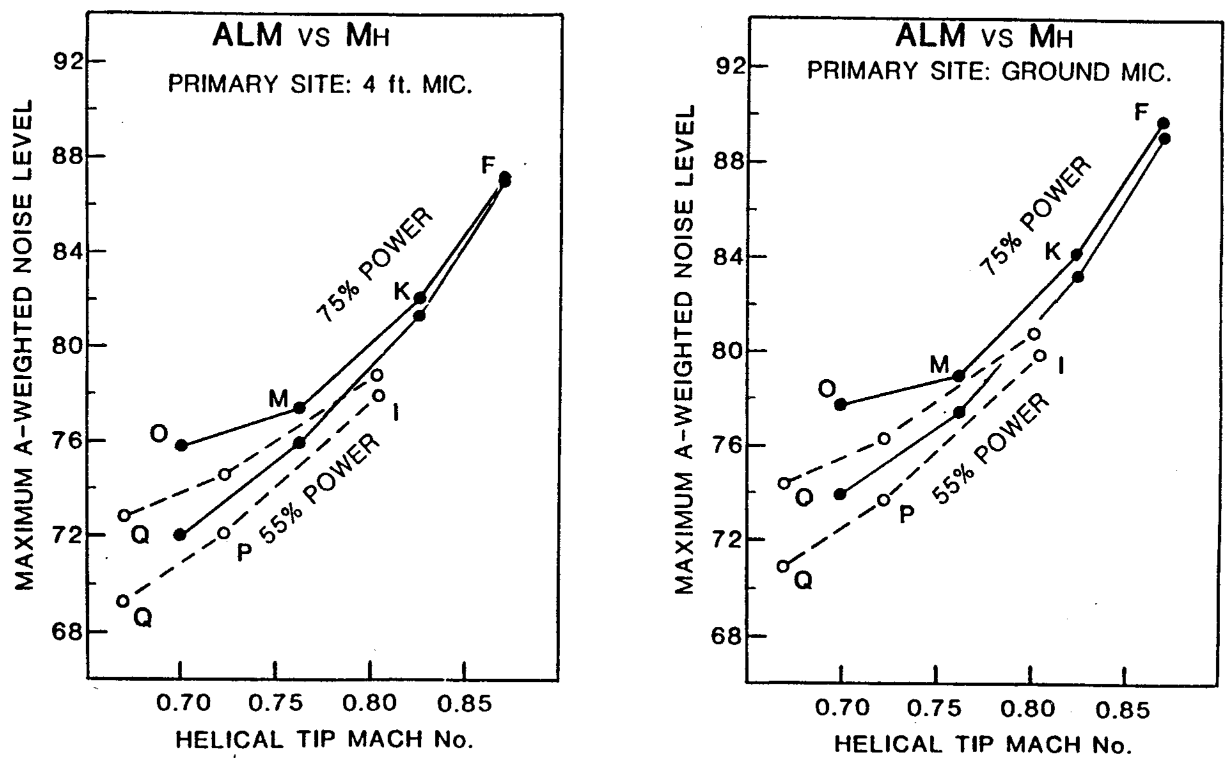
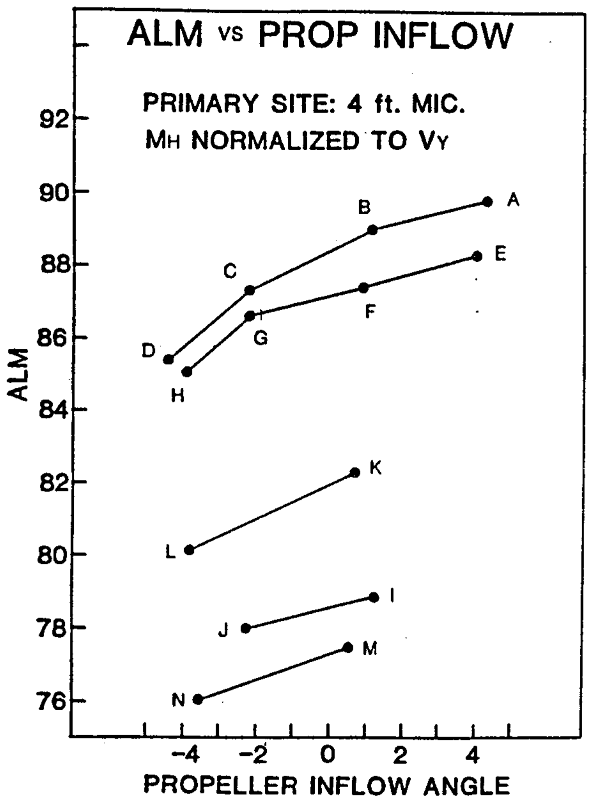


FIGURE 2.42 Effect of Helical Tip Mach Number on A-Weighted Noise at Takeoff (Ref. 2.28)



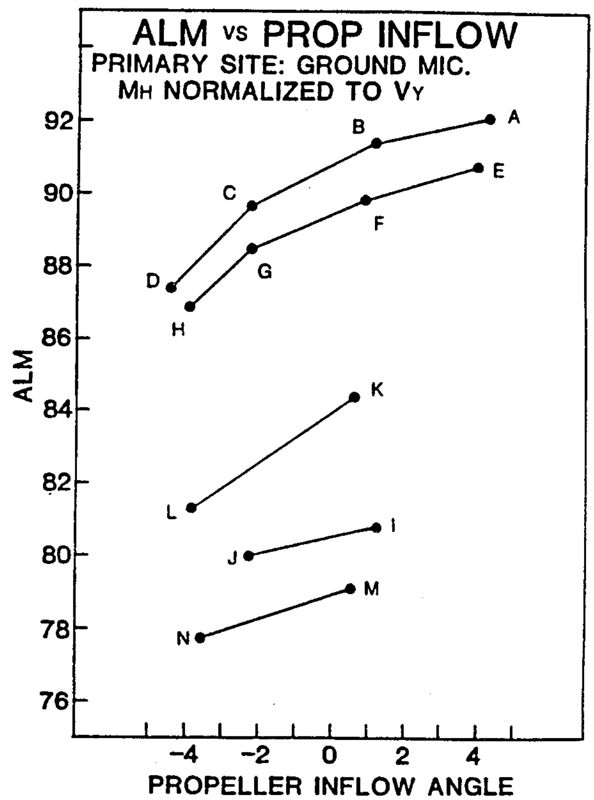


FIGURE 2.43 Effect of Propeller Inflow Angle on A-Weighted Noise (Ref. 2.28)

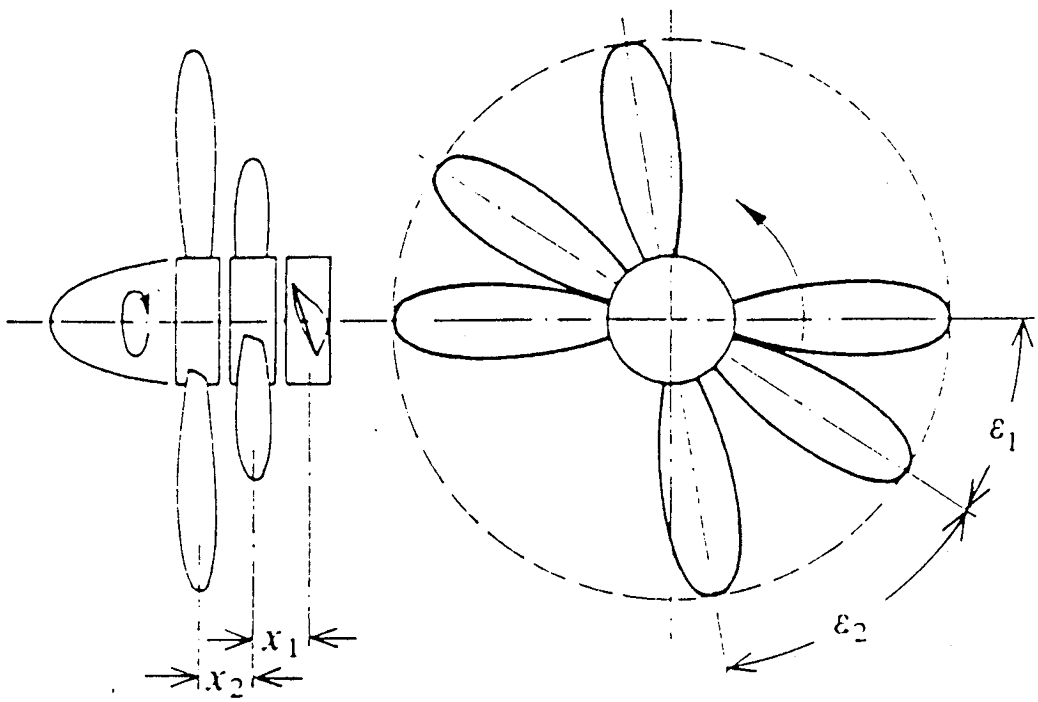


FIGURE 2.44 Schematic of Asymmetrical Spacing Between Stacks of Two Blade Propellers (Ref. 2.30)

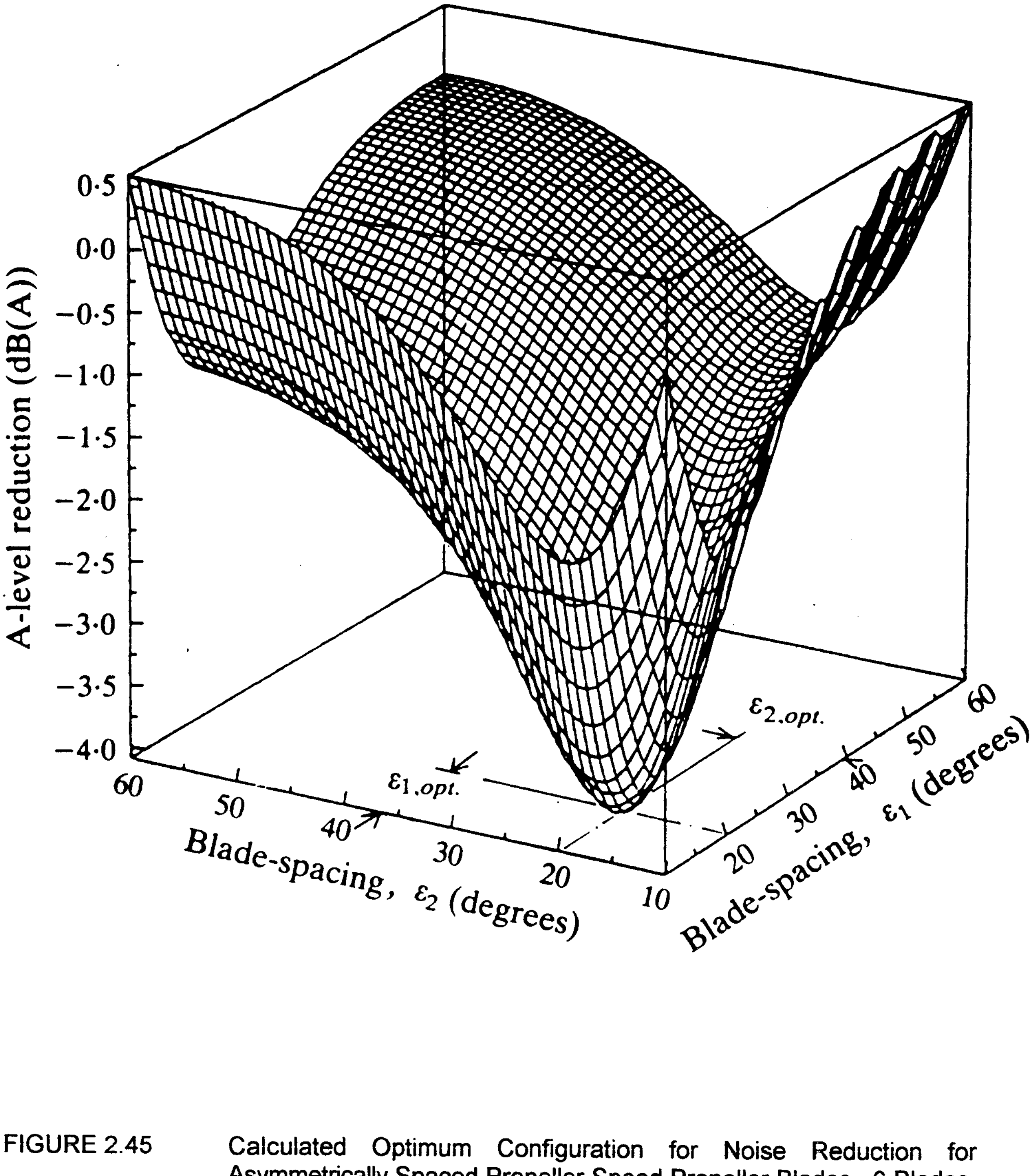


FIGURE 2.45 Calculated Optimum Configuration for Noise Reduction for Asymmetrically Spaced Propeller Speed Propeller Blades , 6 Blades, 3 Meters Diameter (Ref. 2.30)

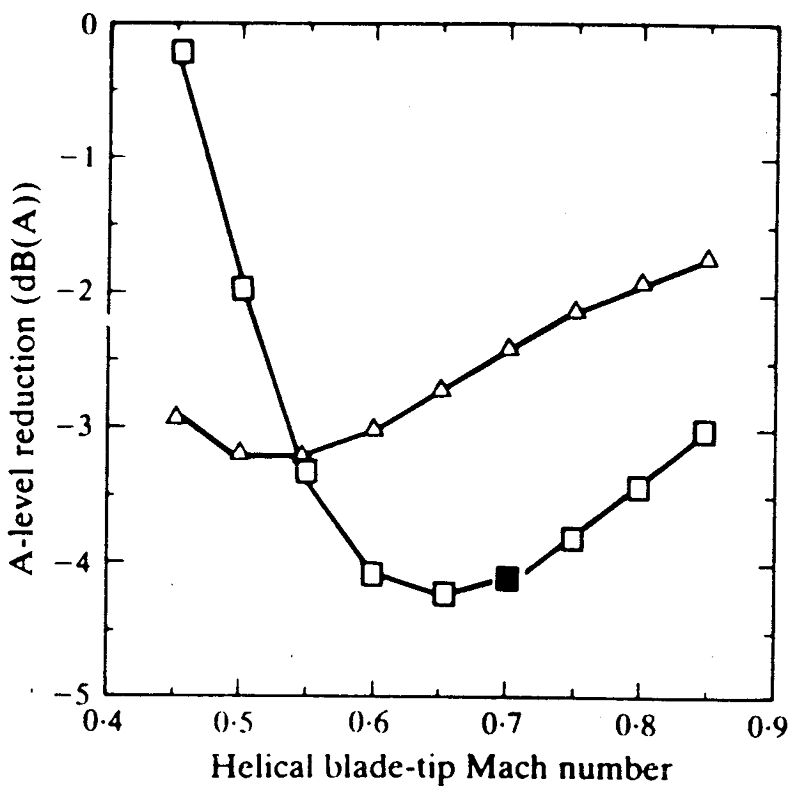


FIGURE 2.46 Effect of Number of Blades on Noise Reduction Potential of a Propeller with Asymmetrically Spaced Blades (Δ Four Blades, □ Six Blades) (Ref. 2.30)

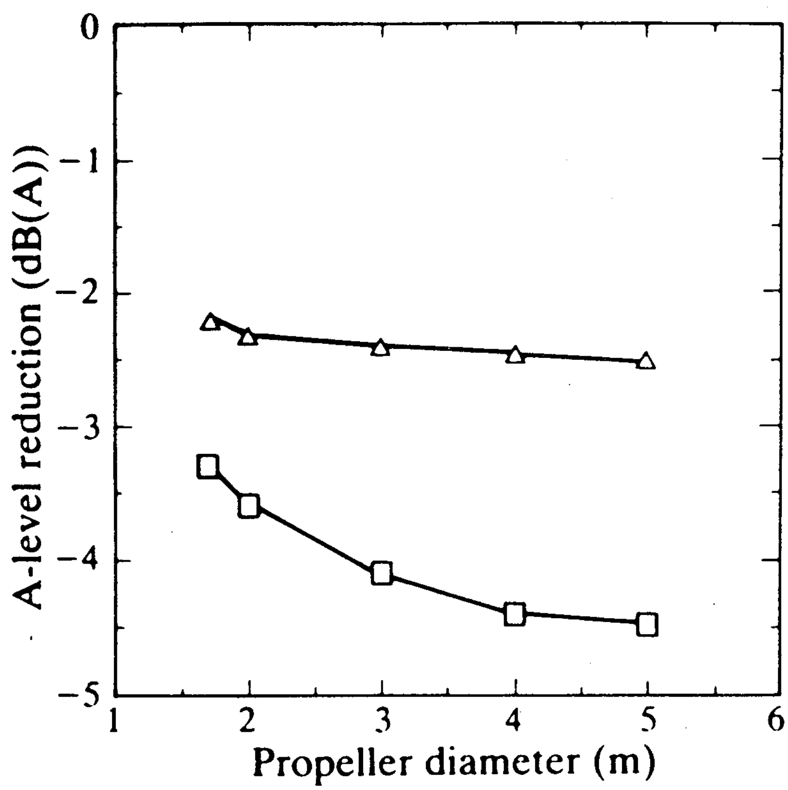


FIGURE 2.47 Effect of Propeller Diameter and Number of Blades on Noise Reduction Potential of a Propeller with Asymmetrically Spaced Blades (Δ Four Blades, □ Six Blades) (Ref. 2.32)

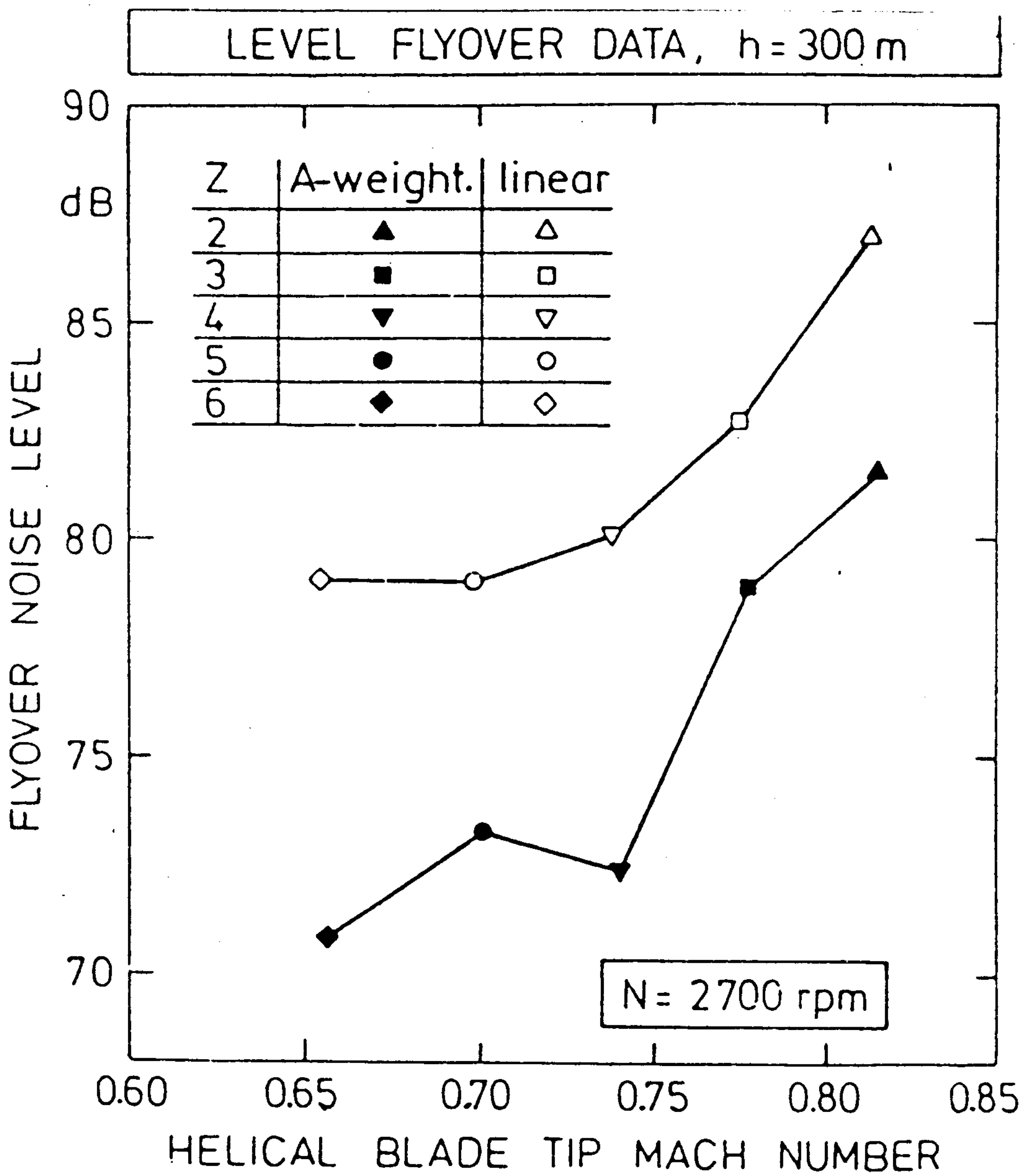


FIGURE 2.48 Effect of Number of Blades on a Max A-Level Flyover Noise (300 ft Altitude) (Ref. 2.37)

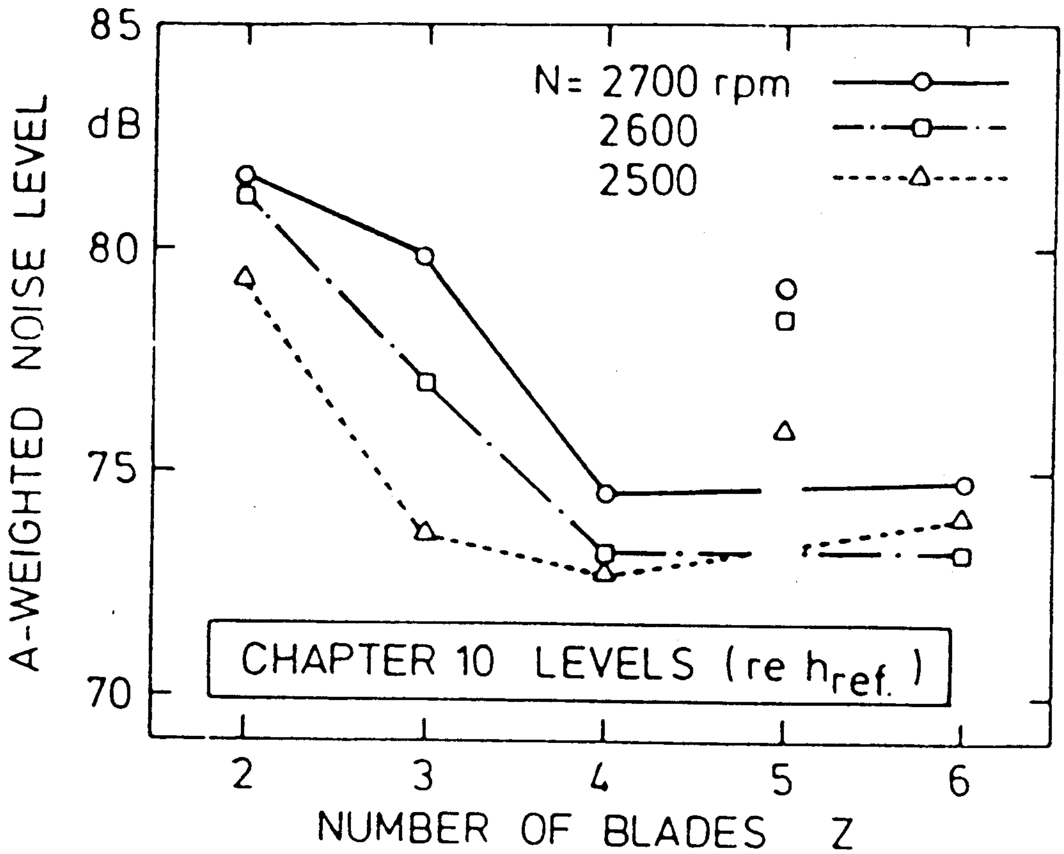


FIGURE 2.49 Effect of Number of Blades and RPM on ICAO Annex 16 Chapter 10 Climbont Noise (Ref. 2.37)

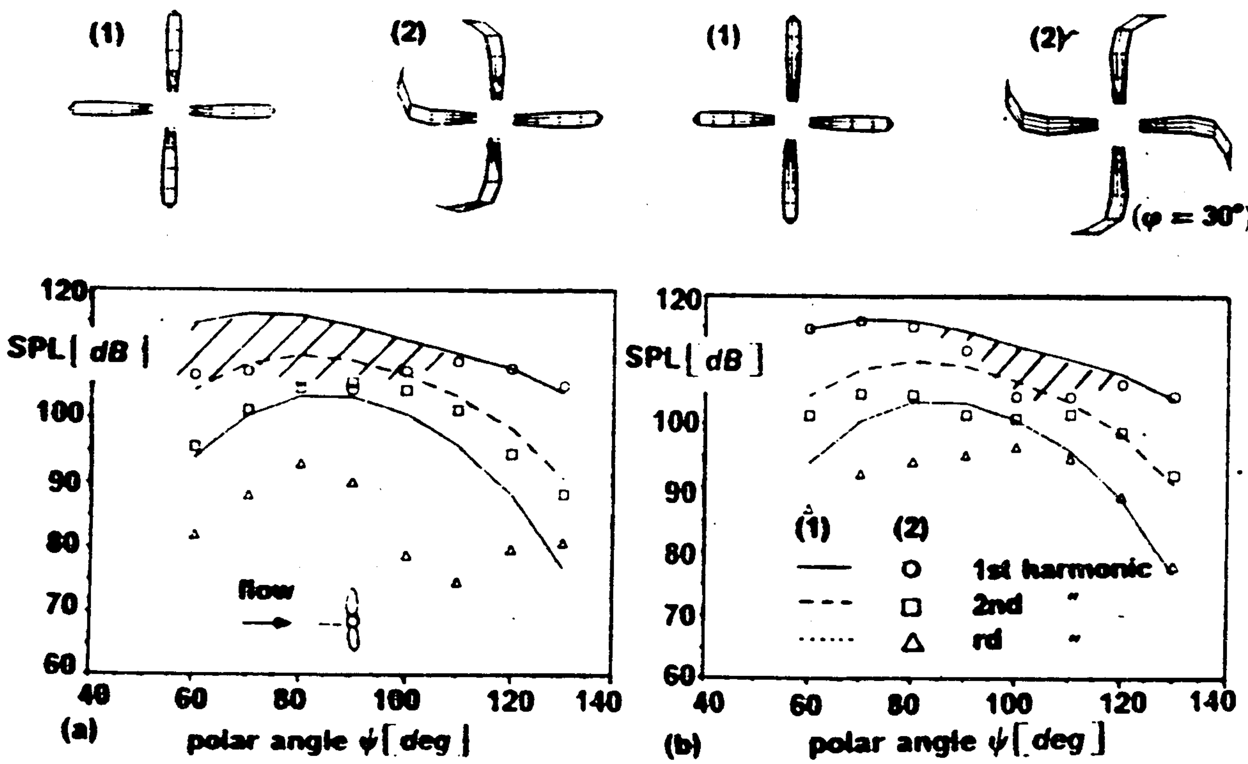


FIGURE 2.50 Noise Reduction Potential Calculated for Propellers having Unsymmetrical Blade Sweep (Ref. 2.38)

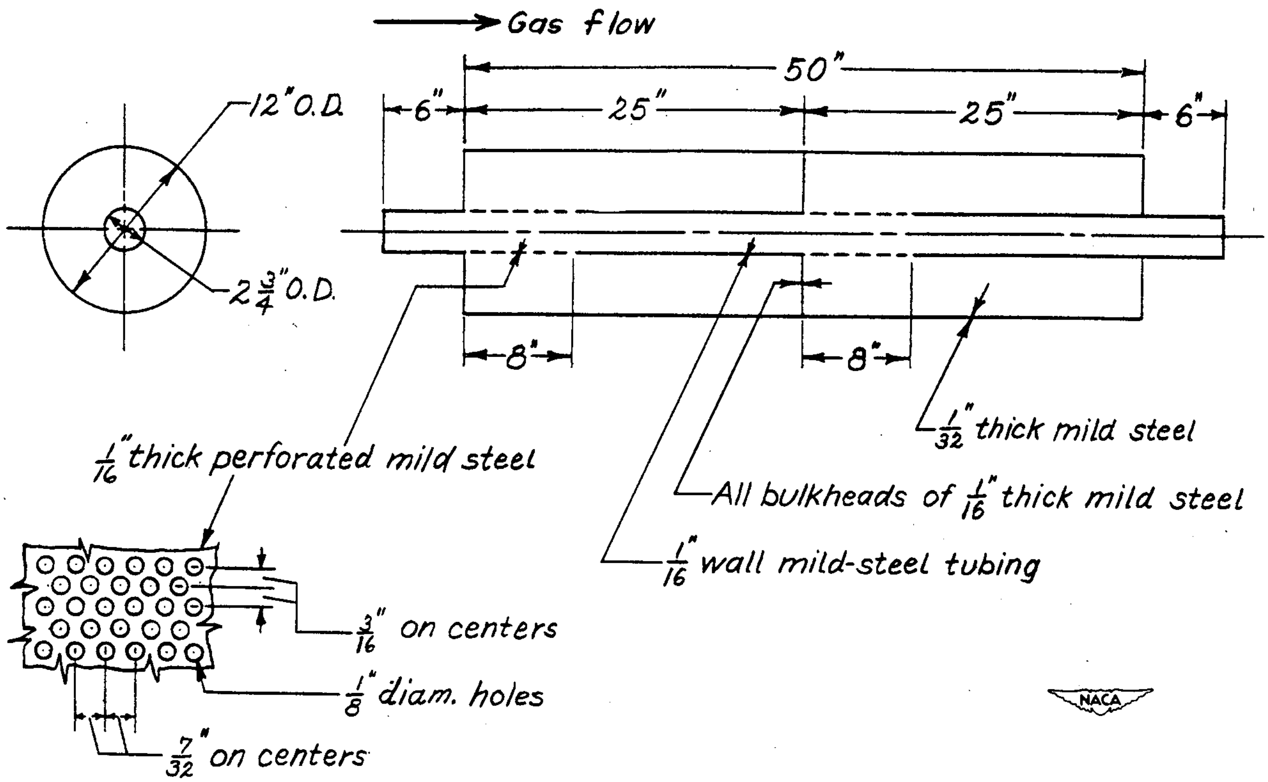
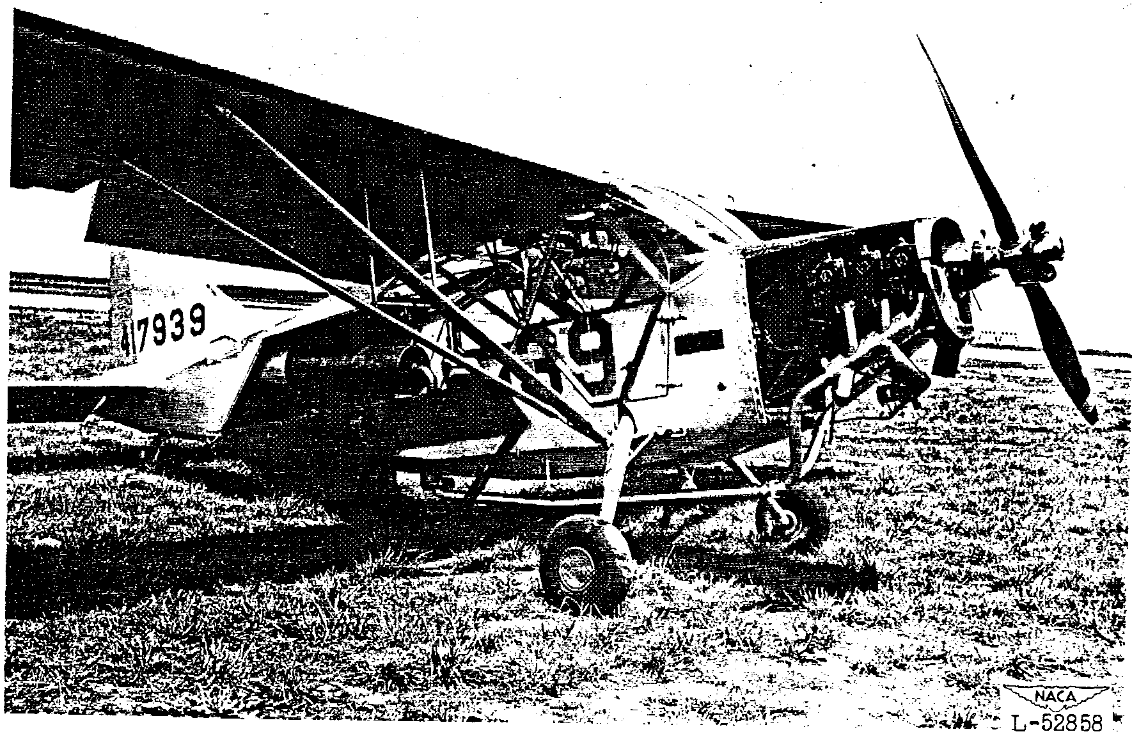


FIGURE 3.1 Configuration of Muffler Used in Vogeley's Flight Test (Ref. 3.3)



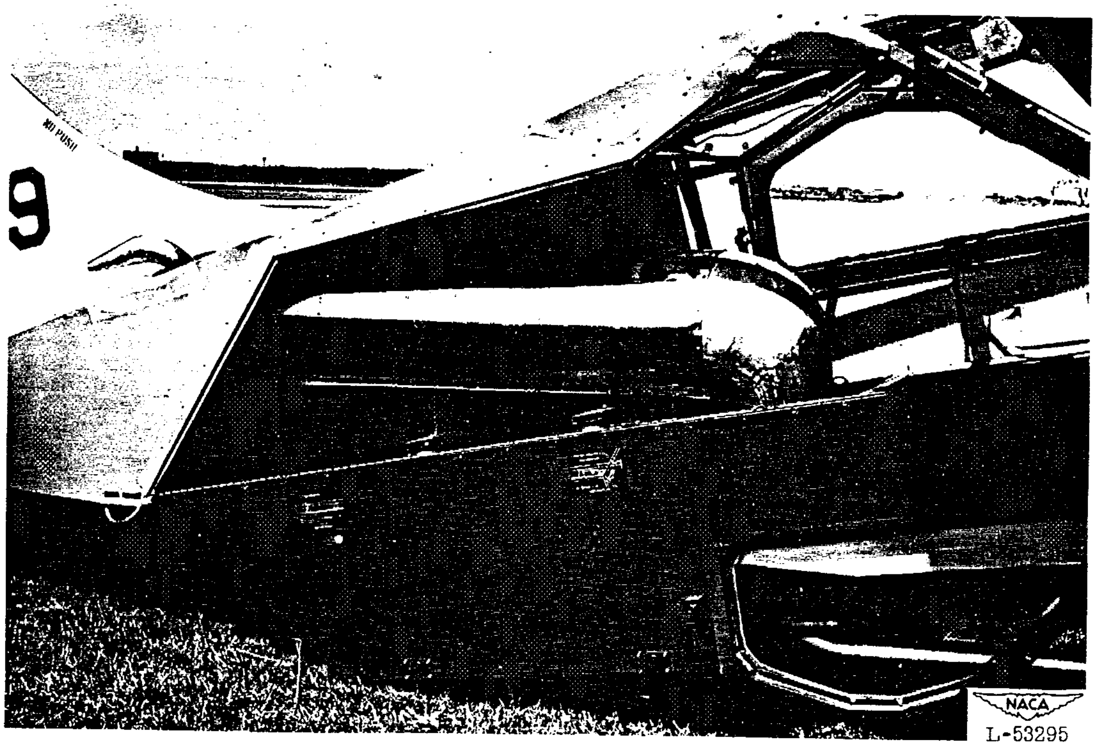
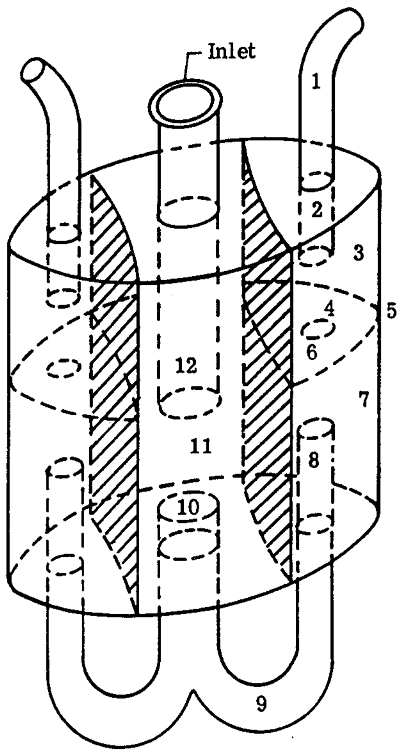
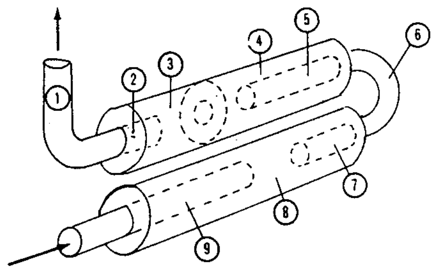


FIGURE 3.2 Installation of Muffler Used in Vogeley's Flight Test (Overall View in Upper Figure, Closeup of Installation with Heat Shield in Lower Figure) (Ref. 3.3)

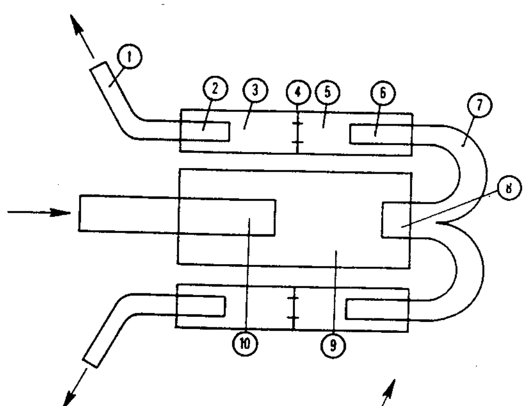


Component	Length, m	Area, m^2
1. Tailpipe	0.60	0.002
2. Extended outlet	.06	.002
3. First chamber	.25	.019
4. Extended inlet	.04	.002
5. Connector	.01	.002
6. Extended outlet	.08	.002
7. Second chamber	.51	.019
8. Extended inlet	.30	.002
9. Connector	.61	.002
10. Extended outlet	.13	.002
11. Third chamber	.76	.019
12. Extended inlet	.44	.002

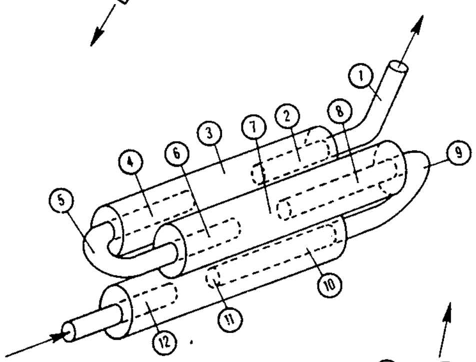
FIGURE 3.3 Schematic of Muffler Configuration (Ref. 3.5)



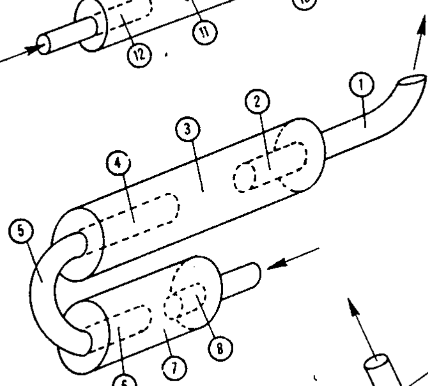
	Length, m	Equivalent area, m^2
① Tail pipe	0.301	0.051
② Extended inlet	.152	.051
③ First chamber	.305	.168
④ Second chamber	.305	.168
⑤ Extended outlet	.381	.051
⑥ Connector	.306	.051
⑦ Extended inlet	.049	.051
⑧ Third chamber	.914	.168
⑨ Extended outlet	.605	.051



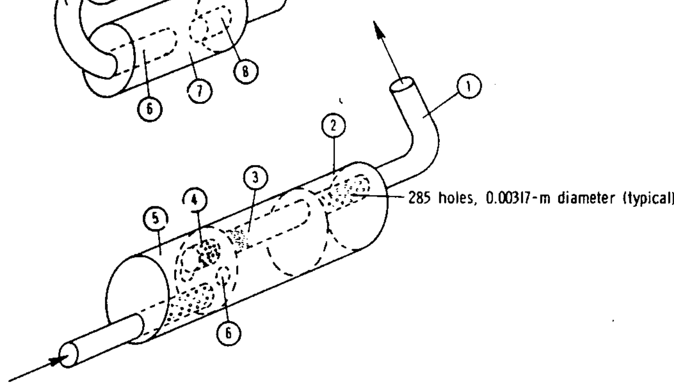
	Length, m	Equivalent area, m^2		Length, m	Equivalent area, m^2
① Tail pipe	0.605	0.051	⑥ Extended inlet	0.301	0.051
② Extended outlet	.058	.051	⑦ Connector	.610	.072
③ First chamber	.253	.155	⑧ Extended outlet	.130	.072
④ Connector	.125	.051	⑨ Third chamber	.765	.184
⑤ Second chamber	.509	.155	⑩ Extended inlet	.443	.072



	Length, m	Equivalent area, m^2		Length, m	Equivalent area, m^2
① Tail pipe	0.475	0.00456	⑦ Second chamber	0.762	0.0127
② Extended outlet	.155	.00456	⑧ Extended inlet	.384	.00456
③ First chamber	.762	.0127	⑨ Connector	.393	.00456
④ Extended inlet	.414	.00456	⑩ Extended outlet	.506	.00456
⑤ Connector	.326	.00456	⑪ Third chamber	.762	.0127
⑥ Extended outlet	.305	.00456	⑫ Extended inlet	.140	.00456



	Length, m	Equivalent area, m^2
① Tail pipe	0.355	0.00457
② Extended outlet	.241	.00457
③ First chamber	.762	.0183
④ Extended inlet	.51	.00457
⑤ Connector	.406	.00457
⑥ Extended outlet	.343	.00457
⑦ Second chamber	.555	.0183
⑧ Extended inlet	.153	.00457



	Length, m	Area, m^2
① Tail pipe	0.209	0.00457
② First chamber	.216	.0365
③ Second chamber	.356	.0365
④ Extended outlet	.025	.00457
⑤ Third chamber	.190	.0365
⑥ Connector hole		.00134

FIGURE 3.4 Helicopter Mufflers Tested (Ref. 3.6)

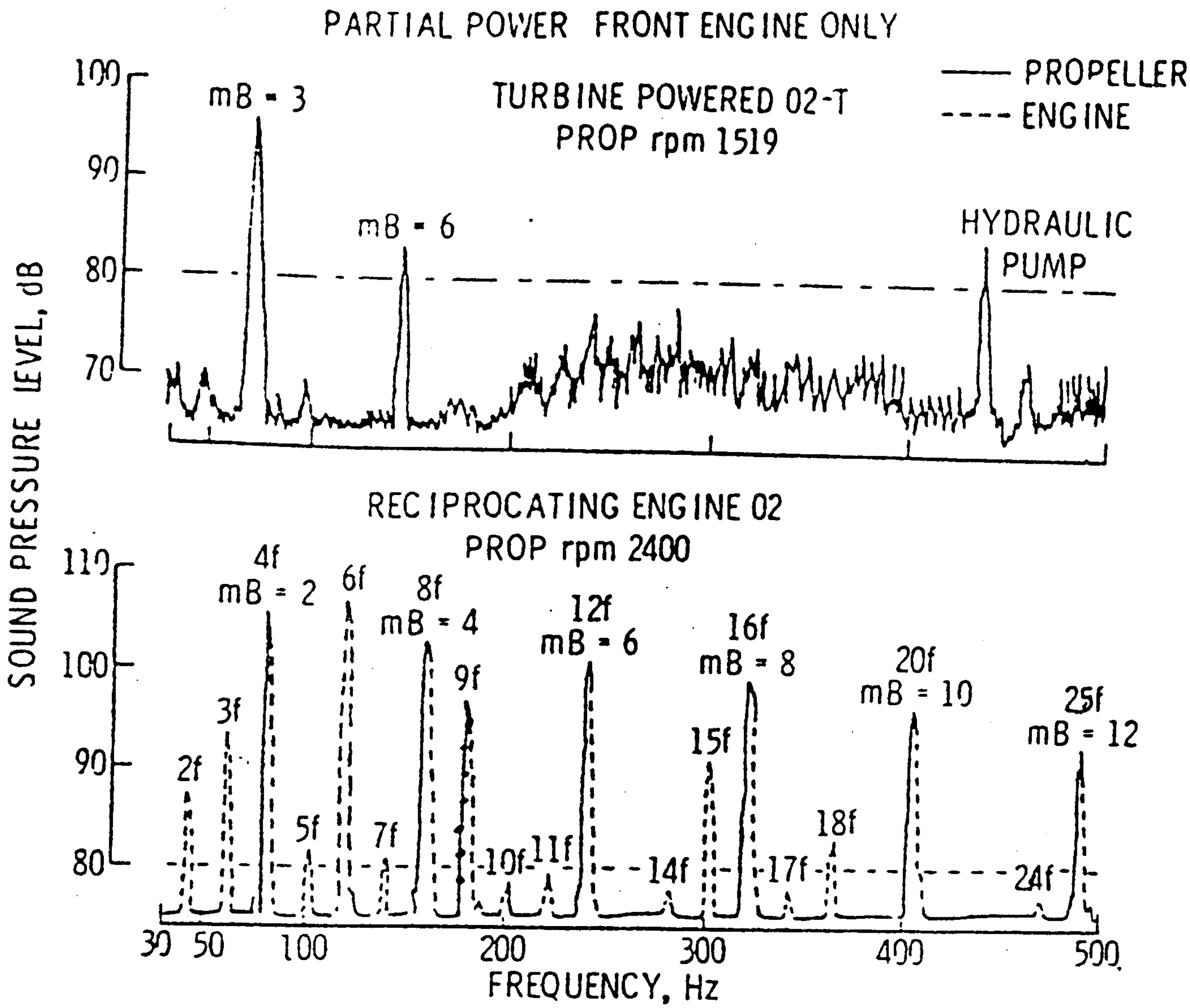


FIGURE 3.5 Noise Spectra of the O-2 Aircraft With Reciprocating Engine Compared with O-2-T Aircraft with Turboshaft Engine (Ref. 3.7)

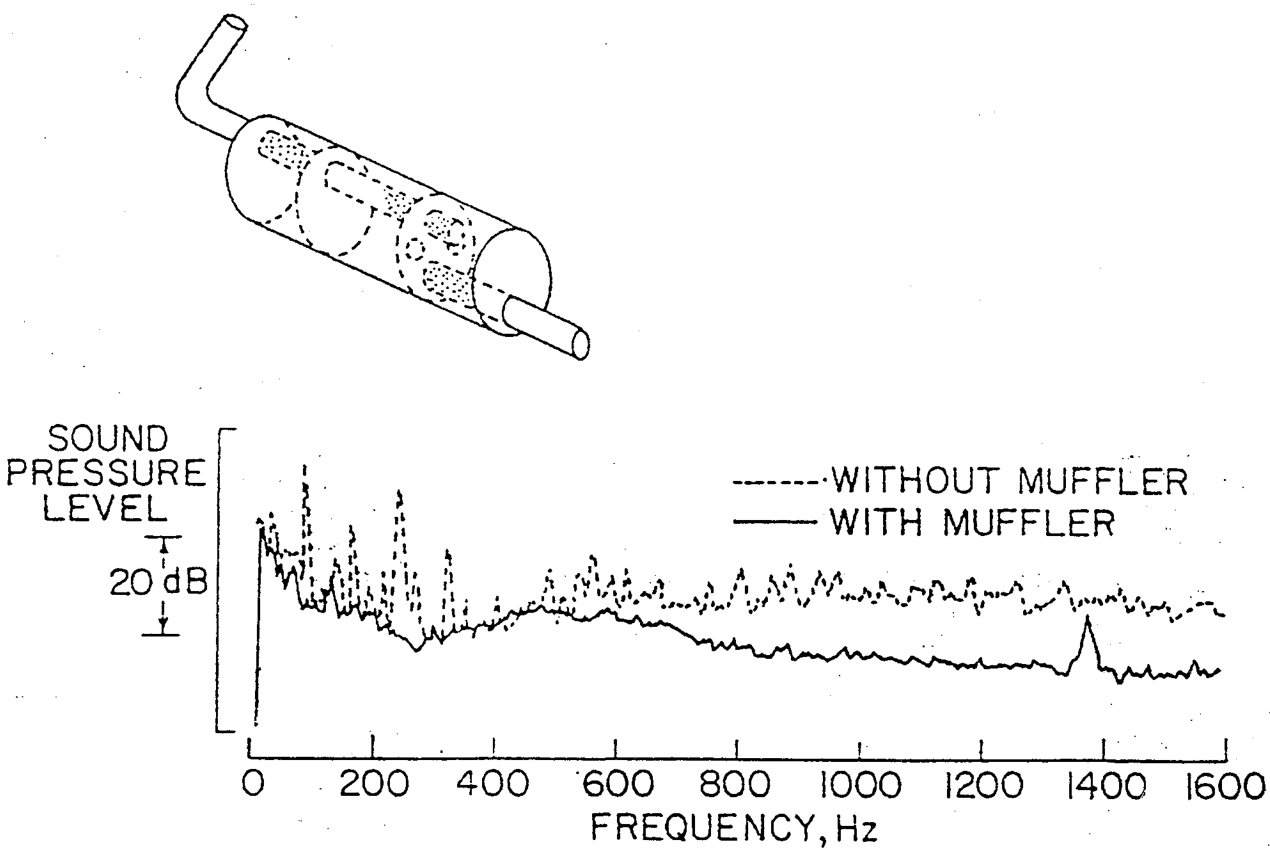


FIGURE 3.6 Effect of Muffler on Exhaust Noise Spectra (Ref. 3.7)

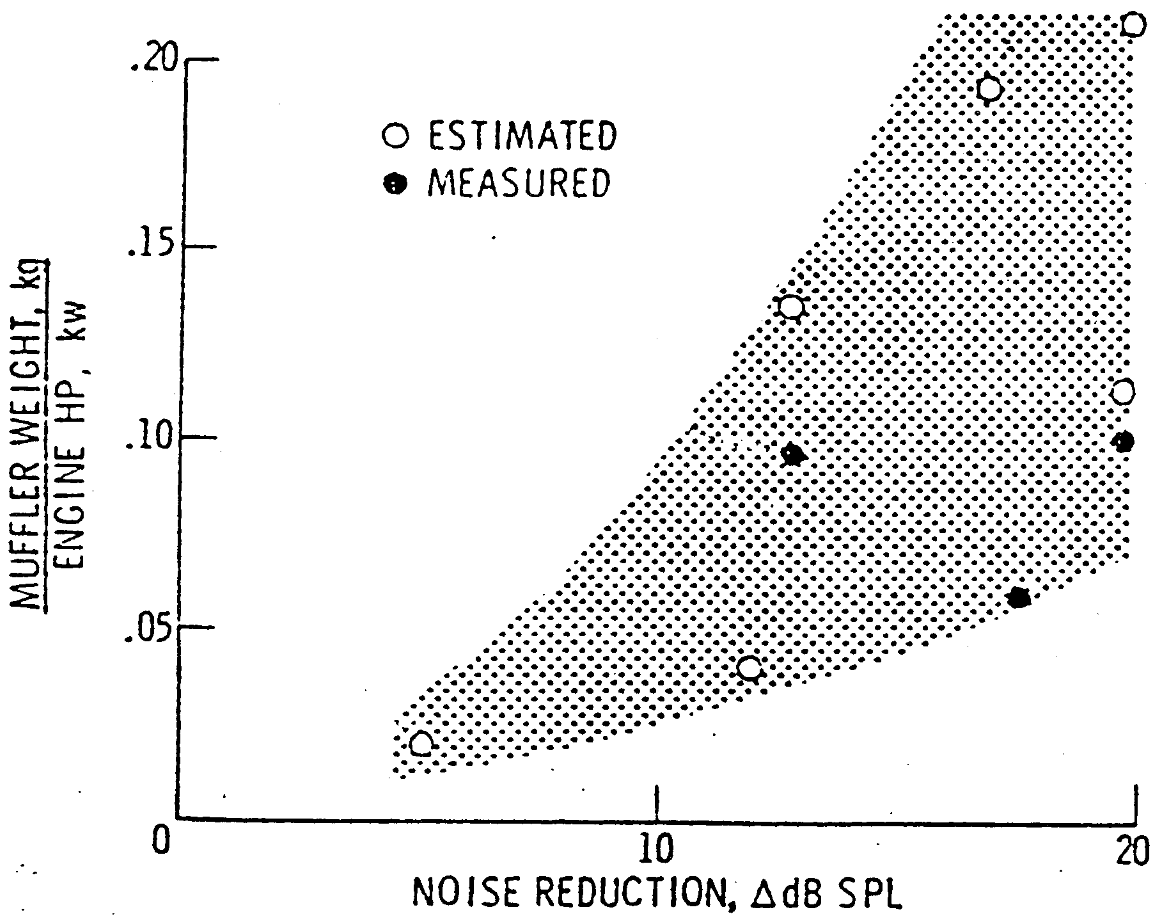


FIGURE 3.7 Generalized Muffler Weight Trend as a Function of Noise Reduction Achieved (Ref. 3.7)

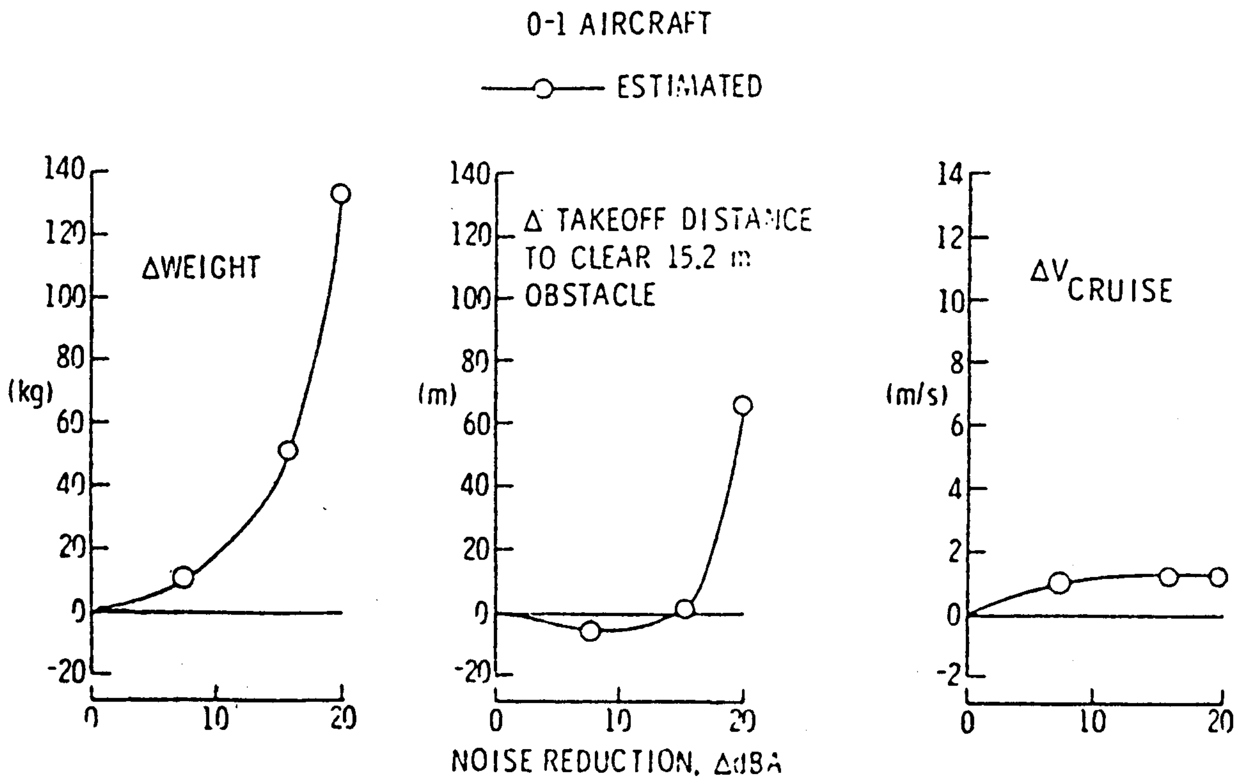


Fig. 16—Effects of various amounts of noise level reduction on the weight and aerodynamic performance of the 0-1 aircraft

FIGURE 3.8 Effect of Noise Reduction on Weight, Takeoff Distance and Cruise Speed of the 01 Aircraft (Ref. 3.7)

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13. ABSTRACT *(Maximum 200 words)*

This report is a review of the literature regarding propeller airplane far-field noise reduction. Near-field and cabin noise reduction are not specifically addressed. However, some of the approaches used to reduce far-field noise produce beneficial effects in the near-field and in the cabin. The emphasis is on propeller noise reduction but engine exhaust noise reduction by muffling is also addressed since the engine noise becomes a significant part of the aircraft noise signature when propeller noise is reduced. It is concluded that there is a substantial body of information available that can be used as the basis to reduce propeller airplane noise. The reason that this information is not often used in airplane design is the associated weight, cost, and performance penalties. It is recommended that the highest priority be given to research for reducing the penalties associated with lower operating RPM and propeller diameter while increasing the number of blades. Research to reduce engine noise and explore innovative propeller concepts is also recommended.

14. SUBJECT TERMS
Propeller, Propeller Noise, Propeller Acoustics, Flyover Noise, Far-field Noise, Propeller Noise Testing, Piston Engine Noise Reduction, Engine Muffling, Mufflers, General Aviation Noise, Propeller Noise Reduction

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