DOE/CE/15277--T1

ALLEVIATION OF FUSELAGE FORM DRAG USING VORTEX FLOWS

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FOREWORD AND ACKNOWLEDGEMENTS

The concept of employing discrete large vortices, to develop favorable cross-flow and to energize the boundary layer in the aft regions of transport aircraft fuselages, was first proposed by the author almost 10 years ago as an apparently original approach to the reduction of fuselage drag. A series of feasibility demonstration proposals, starting with the 1981 USAF DESAT program was submitted to various U.S. Government agencies, but success did not come until favorable evaluations of the concept by the Office of Energy Related Inventions of the National Bureau of Standards led to a recommendation to the Energy Related Inventions Program of the U.S. Department of Energy and a grant for wind tunnel tests. Special thanks are due to D. Mello and T. Levinson of the Department of Energy who monitored this project and guided it through all its administrative and contractual pitfalls.

If this concept is ever deployed commercially, it will be primarily due to M. Rorke of Mohawk Research Corporation and J. Vitullo of the Department of Energy who gave me the opportunity to attend the extremely valuable Commercialization Planning Workshop in August 1987.

The California Institute of Technology 10 ft Wind Tunnel personnel (Jerry Landry in particular) were, as always, extremely helpful and efficient. Finally acknowledgement with thanks is made to the superb efforts of Gayl A. Brinlee without whose assistance and support this concept would not have developed beyond a glimmer of an idea.

SUMMARY

The concept of using vortex generators to reduce the fuselage form drag of transport aircraft combines the outflow from the plane of symmetry which is induced by the rotational component of the vortex flow with the energization of the boundary layer to reduce the momentum thickness and to delay or eliminate flow separation. This idea was first advanced by the author in 1981. Under a DOE grant, the concept was validated in wind tunnel tests of approximately 1:17 scale models of fuselages of Boeing 747 and Lockheed C-5 aircraft. The search for the minimum drag involved three vortex generator configurations with three sizes of each in six locations clustered in the aft regions of the fuselages at the beginning of the tail upsweep. The local Reynolds number, which is referred to the length of boundary layer run from the nose, was approximately 10^7 so that a fully developed turbulent boundary layer was present. Vortex generator planforms ranged from swept tapered, through swept straight, to swept reverse tapered wings whose semi-spans ranged from 50% to 125% of the local boundary layer thickness. Pitch angles of the vortex generators were varied by inboard actuators under the control of an external proportional digital radio controller. It was found that certain combinations of vortex generator parameters increased drag. However, with certain configurations, locations, and pitch angles of vortex generators, the highest drag reductions were 3% for the 747 and about 6% for the C-5, thus confirming the arguments that effectiveness increases with the rate of upsweep of the tail. Greatest gains in performance are therefore expected on aft loading military transports.

Incremental reductions in fuselage drag translate into approximately 1/3 incremental reductions of overall aircraft drag. Therefore, the overall drag reductions are expected to be 1% for the 747 and 2% for the C-5. For the Boeing 747 this translates into annual operating cost reductions of about $130,000. Preliminary estimates indicate that the installed cost of a set of vortex generators will be under $5,000 and maintenance costs of the 2 ft wing-like vanes will be negligible. In terms of return on investment on a low development risk, low installation cost, no maintenance costs project the concept should be extremely easy to deploy commercially.

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INTRODUCTION

Transport aircraft generally follow the form developed by Sir George Cayley almost 200 years ago in having a wing, a fuselage and empennage. The volume of the fuselage is determined by cargo or passenger load requirements with the overall length being fixed by a compromise between operational considerations and aerodynamic efficiency. In general, the aft ends of transport aircraft fuselages are tapered asymmetrically to some minimum base area with a pronounced upsweep of the bottom contour to facilitate rotation in the pitch plane on landing and take-off. The upsweep of the fuselage contour is much more pronounced in aft-loading aircraft such as C-130, C-141, C-5 or the CASA 212. Some representative examples of transport aircraft are shown in Figure 1. Because of the fuselage upsweep, and the rapid decrease of the fuselage cross-sectional area, a strong adverse longitudinal pressure gradient is established. Consequently, the boundary layer on the fuselage grows very rapidly, and may even separate so that a large volume of low energy flow is established around the fuselage. This in turn results in very high momentum defect in the wake and an increase of the fuselage form drag.

The contributions of the various components of an aircraft to the total aerodynamic drag depend on the type of aircraft, mission, and loading. A representative example for a Lockheed C-141 transport at M=0.75 is taken from Nicolai[1] and is shown here in Figure 2. It is seen that the zero-lift drag, C_{Do} is approximately 60% of the total aircraft drag. Nicolai also shows (on p. 2-15) that the zero lift drag C_{Do} may be estimated using

$$C_{Do} \simeq 1.25\ C_{DF} \tag{1}$$

with C_{DF} being the skin friction drag coefficient. With interference drag estimated at 5%, the fuselage form drag in cruise condition is therefore about 10% of the total drag. The effect of reducing the fuselage drag on the reduction of the total drag coefficient is readily estimated from the relation

$$C_D = C_{D,L,t} + C_{Do} = C_{D,L,t} + C_{D,W} + C_{D,F} \tag{2}$$

with

- C_D - total drag coefficient
- $C_{D,L,t}$ - lift and trim drag coefficient
- $C_{D,W}$ - wing drag coefficient
- $C_{D,F}$ - fuselage drag coefficient

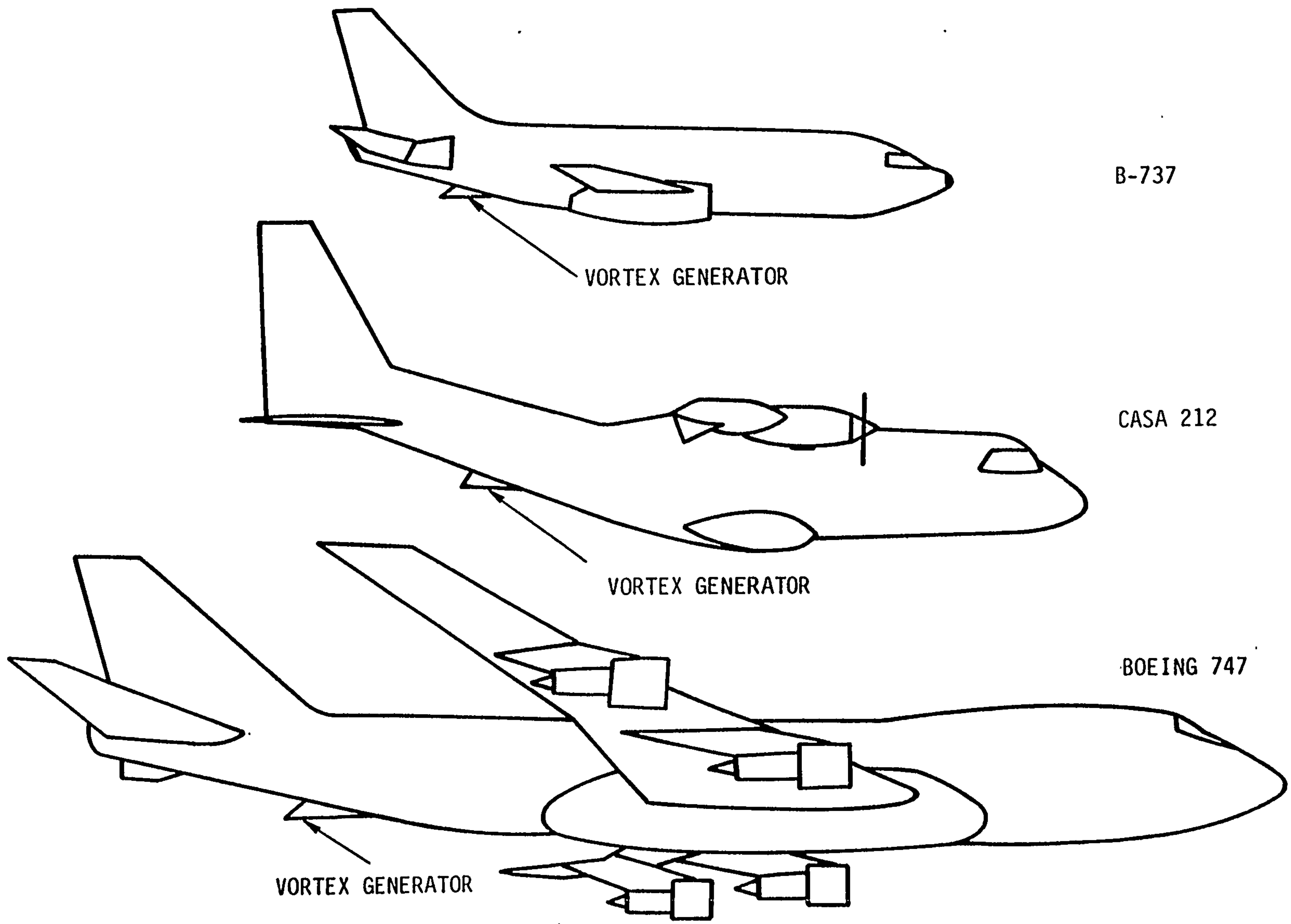


Figure 1. Representative Aircraft Configurations

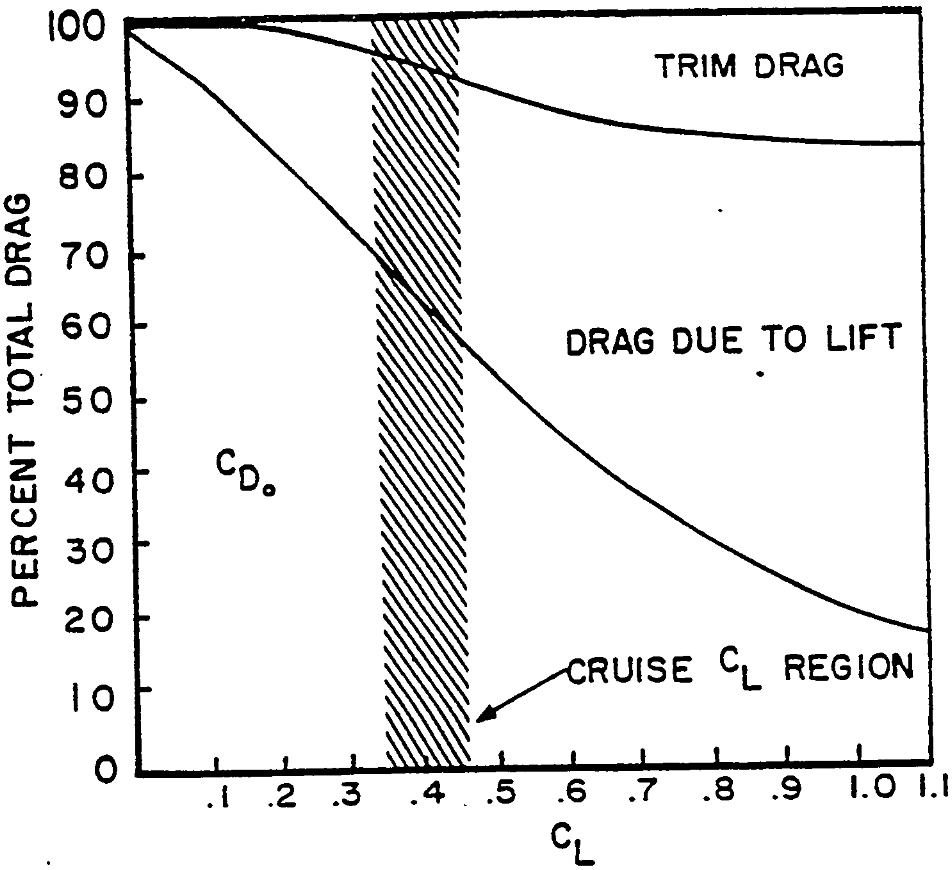


Figure 2. Cruise Drag for C-141

Logarithmic-differentiation yields

$$dC_D/C_D = F^{-1}dC_{D,F}/C_{D,F} \tag{3}$$

with

F - Influence coefficient = $C_{D,L,t}/C_{D,F} + C_{D,W}/C_{D,F} + 1$

The quotients in F may be estimated at being approximately equal to unity. Therefore

$$dC_D/C_D = 1/3(dC_{D,F}/C_{D,F}) \tag{4}$$

This shows that an incremental change in the fuselage drag coefficient results in approximately 1/3 the incremental changes in the total drag coefficient.

Aircraft designs are being continuously refined to enhance their performance and operating economy. When the basic performance and operating requirements are defined, the configurations of the basic components are essentially fixed and only minor shape modifications or additions of appendages are allowed. One of the more attractive approaches is the utilization of vortices to energize the boundary layer and to modify the outer inviscid flow. Attention has focused on aircraft wings where the greatest gains appear to be realizable. An excellent survey of methods for energizing boundary layers to delay or prevent flow separation is given by Pearcey[2]. An example of boundary layer control by means of relatively small vortices is the location of vortex generator "farms" on Boeing 707 aircraft. Large scale vortices on fighter aircraft are generated by means of canards, chines, leading edge extensions or leading edge discontinuities. These can be seen on almost all new aircraft. Small vanes on the forward parts of the projecting DC-10 engine nacelles are yet another example of utilization of vortex generators to control the boundary layers on aircraft wings.

Aircraft fuselages have received less attention, although there is some awareness of the possibilities of drag reduction and flow stabilization. An example of that is the replacement of the tailcone of the McDonnell-Douglas MD-80 by an improved aerodynamic shape which according to Reference 3 reduces cruise drag by about 0.5%. On highly upswept tails of aft loading transport aircraft, the flow instabilities caused by flow separation and vortex shedding have been alleviated through the use of sharp trailing edges and longitudinal strips (Torenbeek[4]) but at the expense of increased drag.

The concept adopted here is a new approach to the reduction of drag of fuselages with upswept tails. It is known that the boundary layer on the upswept part of the fuselage is highly three-dimensional because of the strong retarding axial pressure gradient and inflow towards the vertical plane of symmetry. Such flows were studied by Wortman and Franks[5] who showed that in three-dimensional flows relatively minor inflow towards the plane of symmetry delayed boundary layer separation. The magnitudes of longitudinal adverse pressure gradients causing separation which were far below those observed in two-dimensional flows. Conversely, small outflow from the plane of symmetry increased the resistance to flow separation dramatically. Therefore, rather than merely energizing the boundary layer with an array of small vortex generators, it is much more advantageous to generate two or more large vortices, whose tangential velocity components induce favorable crossflow in the critical region near the plane of symmetry of the fuselage, and also energize the boundary layer.

Preliminary estimates of the required sizes of vortex generators must be derived from order of magnitude requirements since the theory for the interaction of longitudinal vortices with three-dimensional decelerating boundary layers contains too many uncertainties to permit precise calculations. Estimates will be made for M=0.82 cruise at 40,000 ft at a location L = 160 ft from the aircraft nose, and an effective fuselage diameter, D, at that station of 25 ft. The Reynolds number, based on the longitudinal distance, is about 250 x 10^6. Using the relations given by Schlichting[6], it may be estimated that the boundary layer thickness d = 1.25 ft, the displacement thickness d* = 0.15 ft, and the momentum thickness d** = 0.125 ft. The momentum thickness represents the momentum defect due to viscous dissipation in the boundary layer so that the total defect of momentum, M, near the tail is

$$M_D = \pi D d^{**} \rho U^2 \tag{5}$$

with ρ being the density and U the air velocity. Aircraft vortex flows were studied extensively by Wortman[7]. Attention was focused on vortex structure, interactions with viscid-inviscid flows and Reynolds number effects. The study showed that intense vortices have very high axial flow velocities. An example of vortex structure is shown in Figure 3 which is taken from Reference 8.

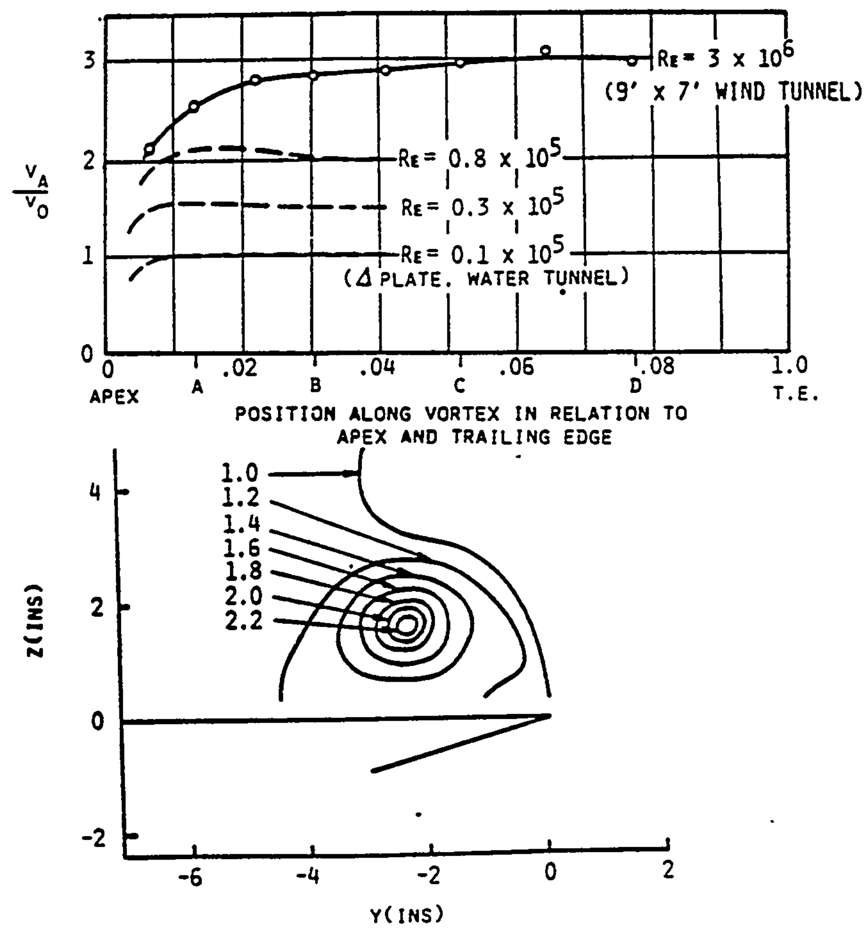


Figure 3. Axial Velocities in a Vortex on a Delta Wing

It is known that the diameter of the vortex at the trailing edge of a delta planform is approximately equal to the half span. Here, the flat plate vortex generators operate at high angles of attack and produce non-linear lift. The shed vortex has a diameter equal approximately to the chord c so that the axial momentum flow in the vortex, M_A, is

$$M_A = \rho Z^2 U^2 \pi c^2/4 \tag{6}$$

with Z being the ratio of average axial velocity to the local free stream velocity. Since the momentum thickness d** is given approximately by

$$d^{**} = .028\ L\ Re_L^{-0.2} \tag{7}$$

with Re_L being the Reynolds number referred running length L at the location of the vortex generators. The ratio of momenta is

$$M_A/M_D = (c^2/LD^*)(Z^2 Re^{0.2}/0.112) \tag{8}$$

With the data from Figure 3 the second group of terms may be estimated to be in the range 2000-5000.

If all of the momentum defect could be recovered by the boundary layer then form drag would vanish. This would be extremely difficult to achieve and a very conservative assumption is made that a reasonable value of the second group is 3000 and that the momentum ratio will have a value of 2. Then

$$c^2/LD = 1/1500 \tag{9}$$

For the vortex generators under consideration, the height, h, to chord ratio is about 2. If the fuselage is treated as a mirror plane, then the effective aspect ratio A = 2h/c is about 4. Therefore

$$(h/D)^2 = (A^2/4)[(L/D)/1500] \tag{10}$$

and h = 0.13D = 3.27 ft. This is an extremely conservative estimate particularly since it does not include the effect of the reduction of the inflow by the vortex tangential velocity. If the upper value of the range of the group in Equation 8 was used and the momentum ratio was taken as unity, then h = .072D = 1.8ft.

A reasonable estimate is probably closer to the latter value rather than the excessively conservative estimate given previously. In any event, a pair of 2-3 ft high fins with chords of 1-2 ft on a 25 ft diameter fuselage does not represent any particular problems of safety or operational capabilities. In fact, wind tunnel studies demonstrated that smaller fins were adequate to achieve significant drag reductions.

EXPERIMENTS

The wind tunnel experimental study was a parametric search for the optimum configuration of vortex generators, locations and pitch angles. The principal parameters were:

a) Vortex generator configurations
b) Vortex generator size
c) Location of the vortex generator
d) Pitch angle of the vortex generators

With 3 configurations in 3 sizes and 6 locations, the total number of runs could be 54, and each run contained at least 5 pitch angles.

Models

The models were approximately 1:17 scale replicas of the fuselages and empennages of Boeing 747 and Lockheed C-5A transports. Hollow, layered clear pine wood construction was employed and structural stiffness of the approximately 13 ft long (4 m) hulls was augmented with steel channel section beams. Details of construction are given in Appendix A. The complete models mounted in the test section of the Cal Tech 10 ft wind tunnel are shown in Figure 4. The size of the models may be gaged from Figure 5.

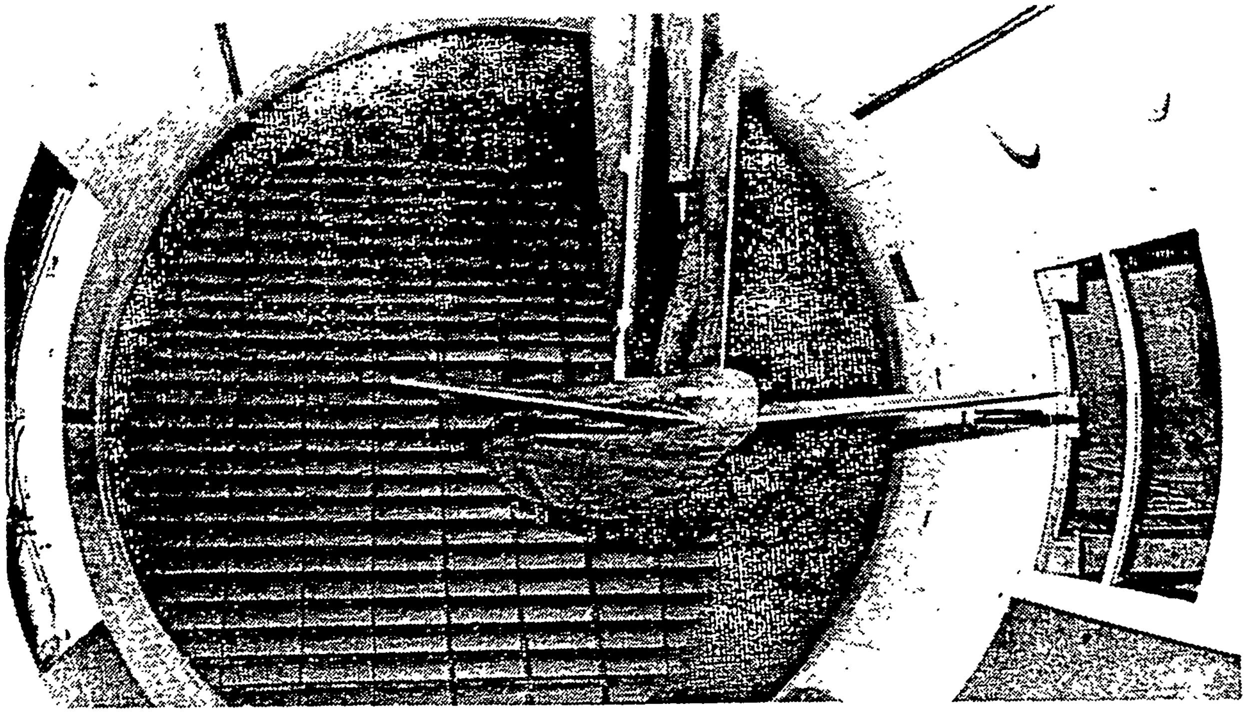


Figure 4a. The B-747 and C-5a Models in the 10' Diameter Wind Tunnel
(Model horizontal surfaces span approximately 5ft)

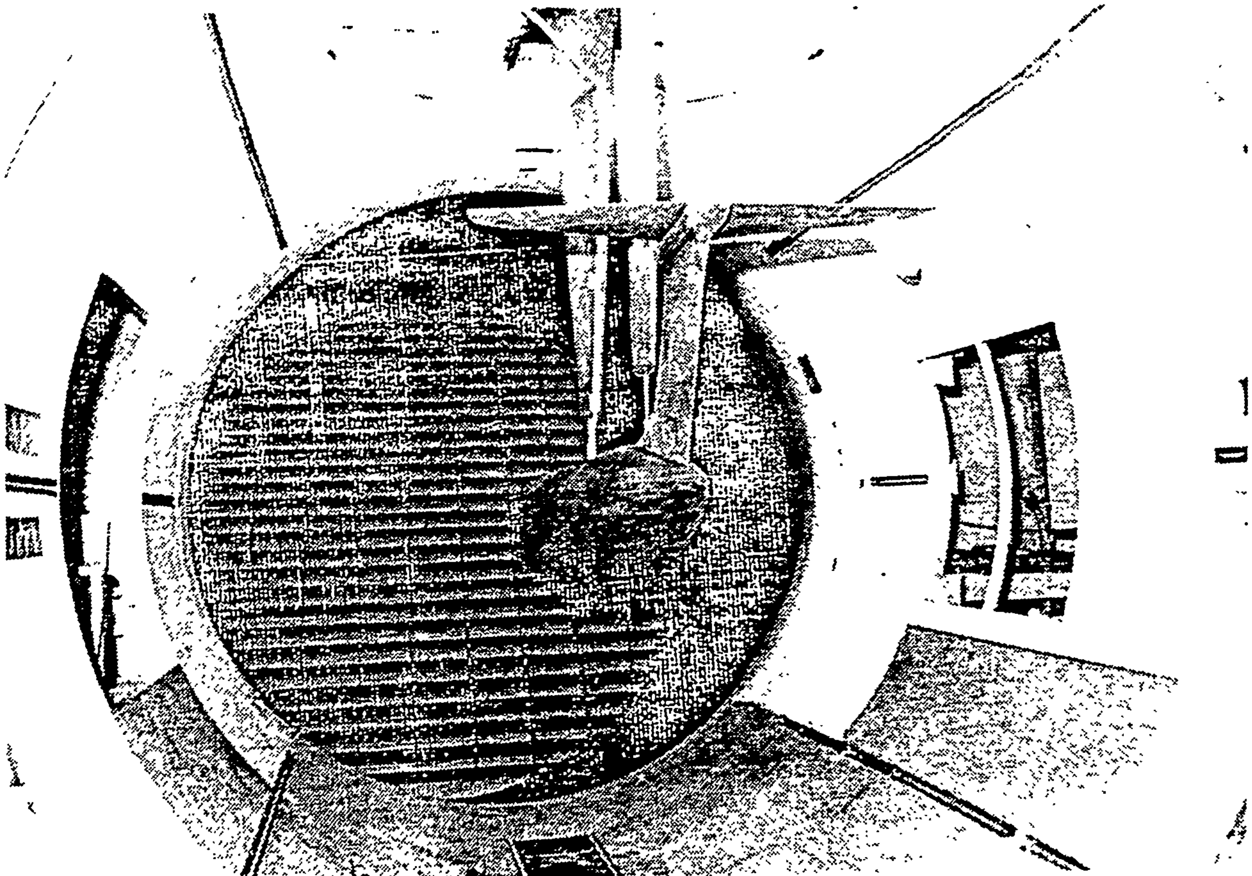


Figure 4. The B-747 and C-5A Models Mounted in the Wind Tunnel (Continued)

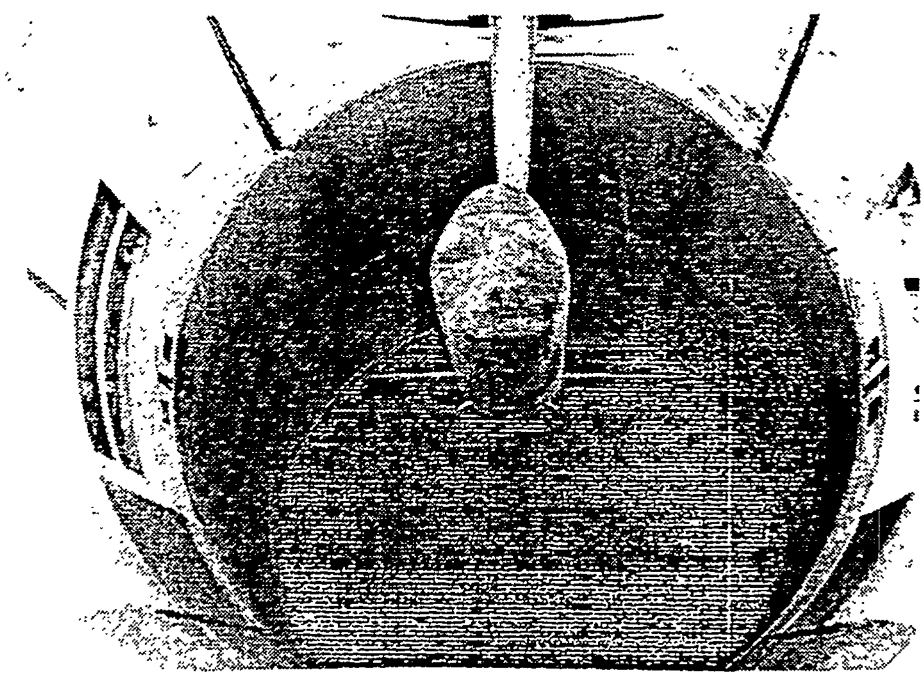


Figure 5. Models in the Wind Tunnel

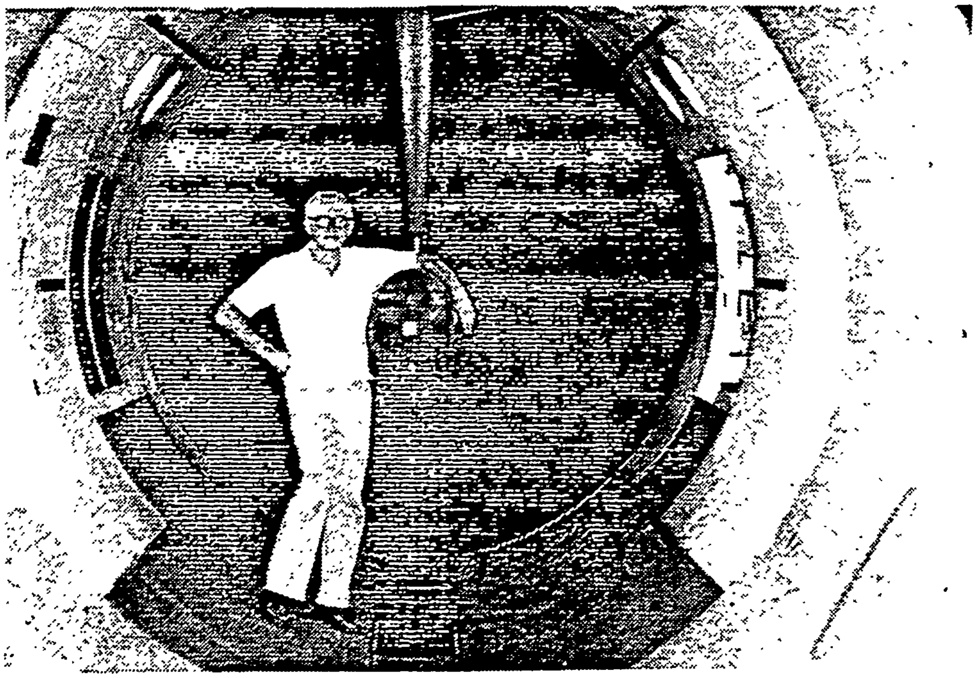


Figure 5b. Models in the Wind Tunnel (Continued)
(Scale may be estimated from the Author's height of 6'2")

Vortex Generators

Three configurations in three sizes each of vortex generators were tried. These are shown in Figure 6. The vortex generators were made of 0.06" (1.5mm) brass sheet and were brazed to brass tube axles which attached by means of screws to the actuating mechanisms inside the fuselages. Installation of vortex generators is shown in Figure 7. Location and relative sizes are shown in Figure 8.

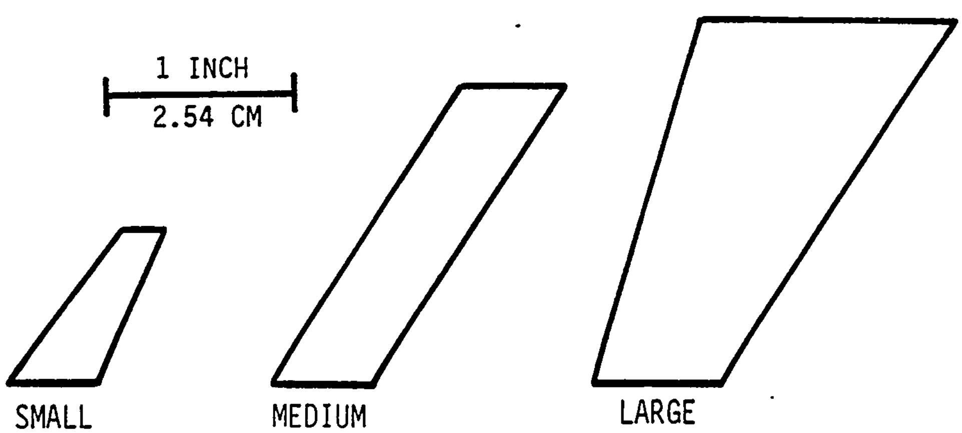


Figure 6. Vortex Generator Configurations and Sizes

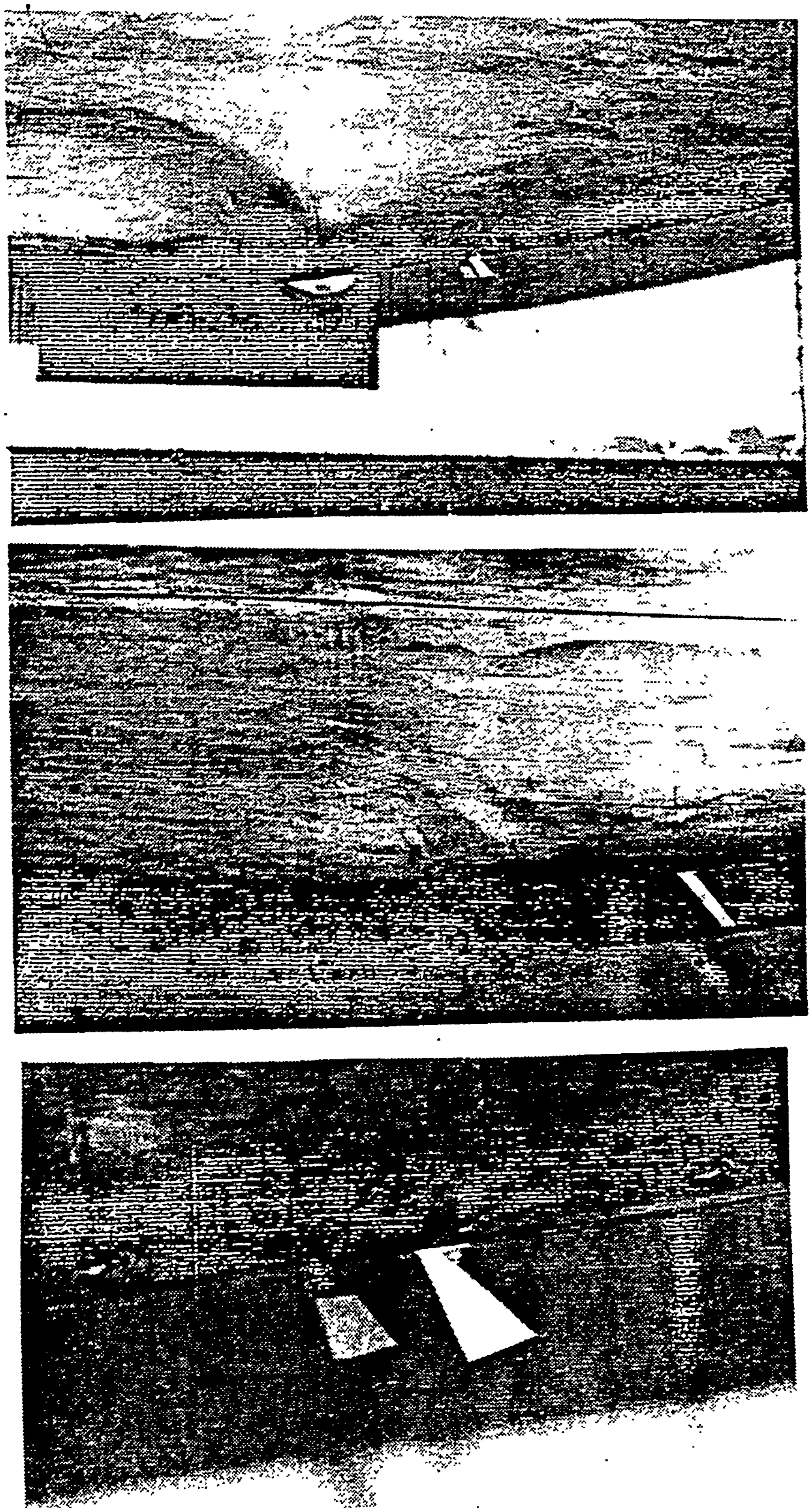


Figure 7. Vortex Generator Installation
Largest Vortex Generators Span 2" (5cm)

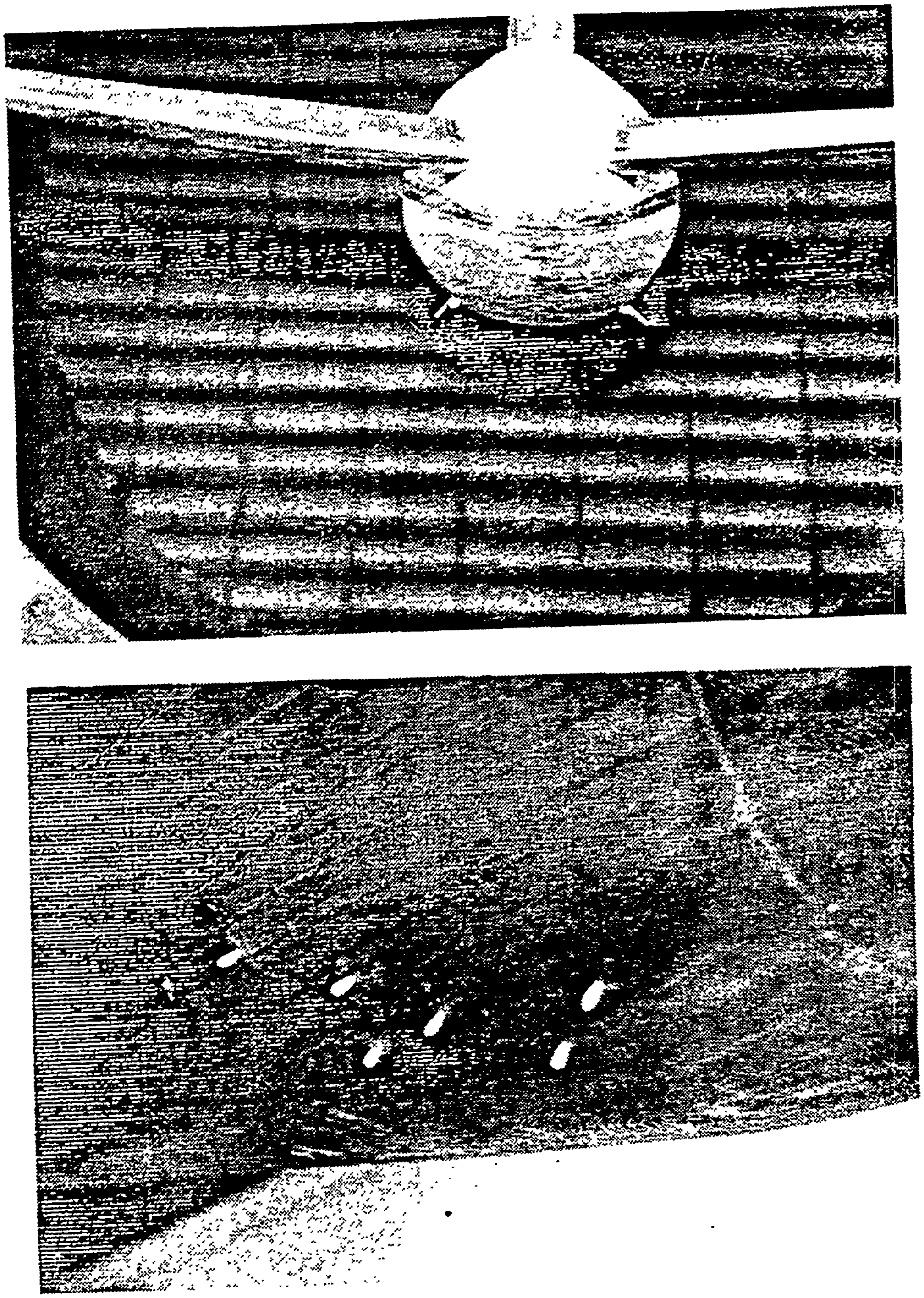


Figure 8. Vortex Generator Installation, Locations and Relative Sizes (Vortex generator span is 1.5". Locations are at the fuselage break. The view is downstream)

Controls and Actuators

Control of the pitch angles of the vortex generators was by means of a Futaba proportional digital radio transmitter located outside the wind tunnel and a receiver mounted in the tunnel wall. Pitch angle changes were made by Futaba actuators controlled by a proportional digital radio controller operating sets of rods and bell cranks. Only one pair of vortex generators was actuated at any time. All actuating mechanisms were in removable fuselage sections so that adjustments and repairs could be made without interfering with the mounting of the models in the wind tunnel.

Procedure

After a pair of vortex generators was installed on the model, their pitch angle was set to base value (0 on the controller) and the wind tunnel was started. The base pitch angle was set at an estimated $+10^{\circ}$ to the guessed local streamline with positive pitch being defined when the leading edge of the vortex generator was outboard of the local streamline. Pitch angles were changed in increments of 25% of the controller scale until at 100% the estimated pitch angle was -30°. After each pitch change, the tunnel was run for 5-10 minutes to allow the balances to stabilize.

Wind Tunnel

The tunnel used for these experiments was the California Institute of Technology 10 ft Wind Tunnel Facility. This is a recirculating flow tunnel capable of speeds up to 250 ft/s. The facility has a 6 degree of freedom model support system and the balances have a resolution of 1 count. After each change in the vortex generator pitch angles, the balance system was allowed to stabilize for a few minutes until variations in the readings were essentially constant. In these tests only lift and drag data were recorded.

Test Aerodynamics

The Boeing 747 model was tested at a dynamic pressure of 30 psf because of some concerns related to possible aeroelastic problems. The much more rigid C-5 model was tested at 60 psf. The corresponding velocities are approximately 160 ft/s and 225 ft/s respectively. In the regions where the vortex generators were located, the Reynolds numbers referred to the axial distance from the nose were 9.5×10^6 for the Boeing 747 and 11.2×10^6 for the C-5. There was no doubt that the boundary layer was fully turbulent in the vicinity of the vortex generators, but a boundary layer tripping strip shown in Figure 9 was used on some tests. No differences in drag could be detected in the tests with and without the trip and the use of the latter was abandoned.

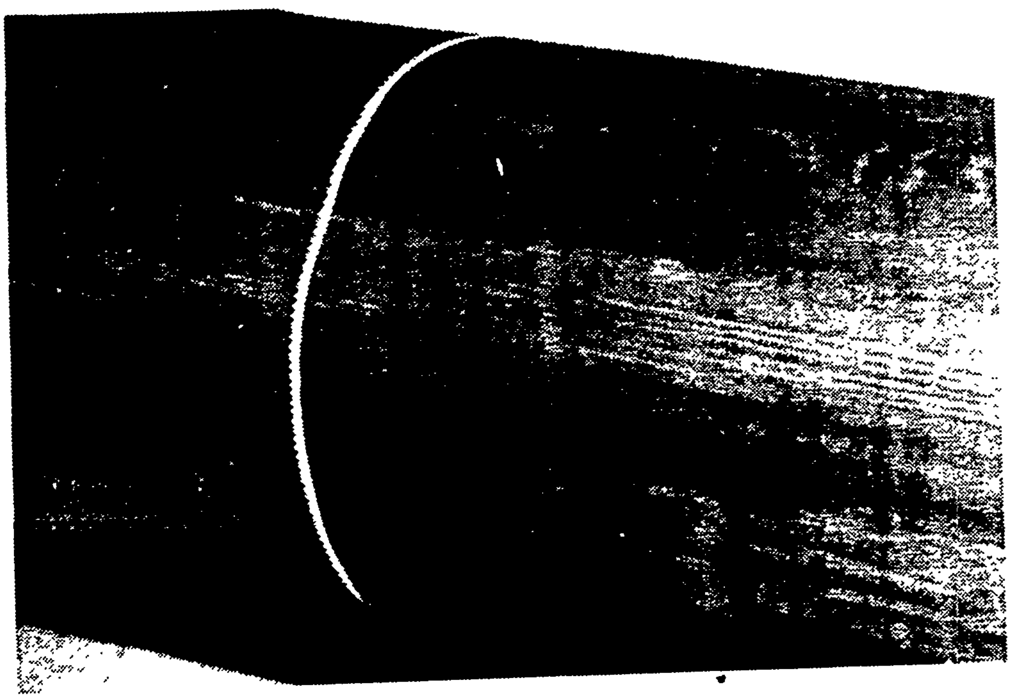


Figure 9. Boundary Layer Tripping Strip
(Fuselage Depth is Approximately 18")

Flow visualization by means of arrays of tufts was tried on a few runs. Representative examples are shown in Figure 10. The slight fluttering of the tufts near the fuselage centerline on bare fuselages was alleviated noticeably when vortex generators were rotated to their optimum pitch angles. These observations indicate that while there is no flow separation, the boundary layer is retarded and somewhat unsteady. Reduction, or elimination of this unsteadiness by the vortex generators, indicates that the concept of imposing longitudinal and transverse velocities on the boundary layer is an effective aerodynamic flow modification.

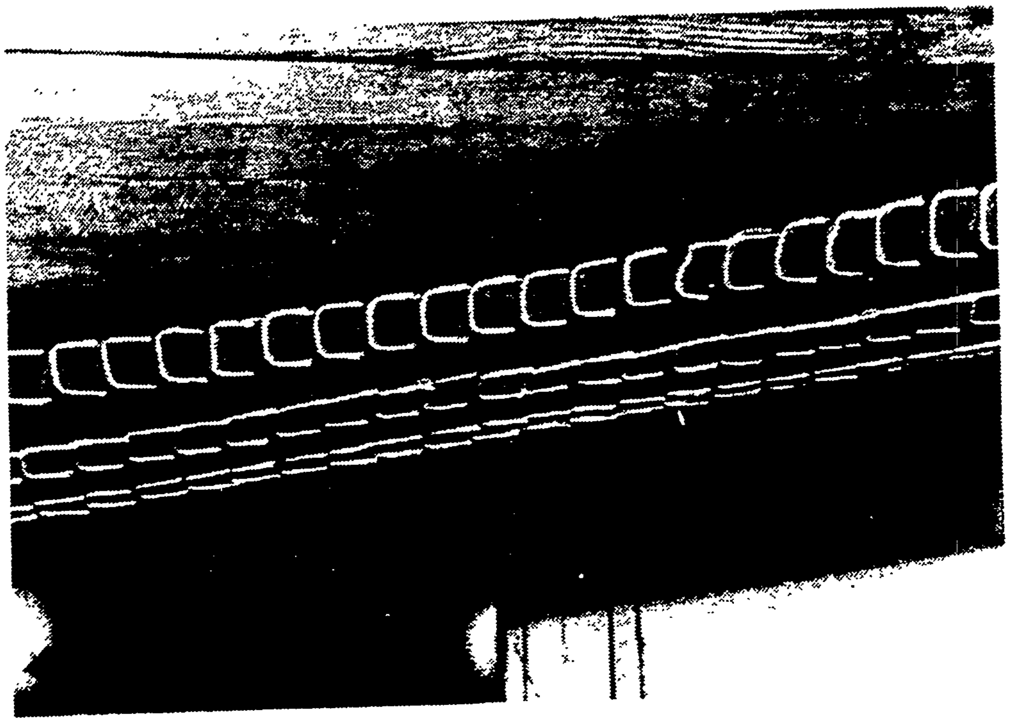


Figure 10. Flow Visualization Tufts

For the Boeing 747 model the boundary layer parameters at the location of the vortex generators are estimated to be:

Thickness	=	1.6 inches (4 cm)
Displacement Thickness	=	0.2 inches (.5 cm)
Momentum Thickness	=	.15 inches (.4 cm)

For the C-5 model the boundary layer parameters are estimated to be 80% of the above values. Vortex generator heights ranged from 3/4 inches to 2 inches. Even for the smallest vortex generators, the flow velocity at their outer tips was at over 85% of the local inviscid flow velocity. The vortices were therefore generated by flows with relatively high dynamic pressures.

RESULTS

Wind tunnel data are summarized in Appendix C in terms of "counts" of the tunnel balances. In this case, the interest is focused on differences rather than absolute values. Selected values of the best configurations are shown in Tables 1A and 1B. Lift and pitching moments were also monitored in all the runs and it appears that these were not affected perceptibly by the vortex generators.

Table 1A. Selected B-747 Drag Data

RUN #	VORTEX GENERATOR #	SIZE	STATION #	DRAG COUNTS
1	--	--	---	2234
*10	3	L	1	2169
22	3	M	4	2186
29	1	S	2	2166
32	2	S	2	2179
35	3	S	2	2182
41	1	S	4	2177
47	1	S	6	2183
52	3	S	6	2183
58	1	S	2	2181
*64	3	L	1	2173

Notes - S - small, M - medium, L - large
- * Duplicate runs 5 days apart

Table 1B. Selected C-5 Drag Data

RUN #	VORTEX GENERATOR #	SIZE	STATION #	DRAG COUNTS
66	--	--	---	1812
*80	1	L	1	1766
*81	1	L	1	1768
82	3	S	1	1761
83	3	M	1	1737
84	3	L	1	1735
85	3	S	3	1755
86	3	M	3	1749
87	3	L	3	1743
89	2	M	4	1735
92	3	S	5	1738
93	3	M	5	1736
94	3	L	5	1744
95	2	S	5	1743
96	2	M	5	1710
97	2	L	5	1733
98	1	M	5	1734

Notes - S - small, M - medium, L - Large
- * Duplicate runs to check consistency

The data indicate that a 3% reduction in fuselage drag can be achieved for the Boeing 747 and almost double that reduction can be realized for the Lockheed C-5. These values do not necessarily represent the absolute maxima because of the limited number of configurations, sizes, locations and pitch angles which could be tested. It is quite likely that greater drag reductions could be found, but at the expense of additional locations and vortex generator configurations. The required wind tunnel test time would increase rather significantly. This was far beyond the means of the present project.

The problem of finding optimum vortex generators is quite formidable but not beyond the reach of a reasonable engineering effort. It is shown in the data in tables 1A and 1B that quite similar results can be achieved by different vortex generators in different locations. When optimum pitch angles were sought during the test by making small pitch changes around the optimum value, it was found that the sensitivity was very low. This reduces greatly the efforts to find optimum pitch angles.

FULL SCALE IMPLEMENTATION

Scaling of wind tunnel results to full scale actual aircraft applications can be accomplished in several ways. If purely geometrical scaling is adopted then the vortex generators would be approximately 2 ft (60 cm) high. Scaling on the ratio of vortex momentum to the boundary layer momentum defect requires that

$$(A_V/Dd^{**}) = \text{constant} \tag{11}$$

with

A_V - vortex generator area
D - local fuselage diameter
d^{**} - boundary layer momentum thickness

In terms of Reynolds numbers

$$Re_L^{0.2}\, A_V/LD = \text{constant} \tag{12}$$

With wind tunnel $Re_L = 10^7$ and full scale $Re_L = 25 \times 10^7$ the relation

$$(A_V/LD)_{Prototype} = 0.525\ (A_V/LD)_{Model} \tag{13}$$

This leads to the conclusion that the vortex generators on full size aircraft should be 0.725, their relative size on the wind tunnel models. Several other approaches to translating wind tunnel vortex generator sizes to full scale applications are possible, but they all lead to the conclusion that on Boeing 747 and Lockheed C-5 aircraft, the height of the vortex generators should be about 2 ft. An appreciation of the relatively small sizes which are required may be gained from the consideration that the Boeing 747 is approximately 220 ft long and in the region of the vortex generators the effective fuselage diameter is about 25 ft. Relative size may also be gauged from an installation on the C-5 model which is shown in Figure 11.

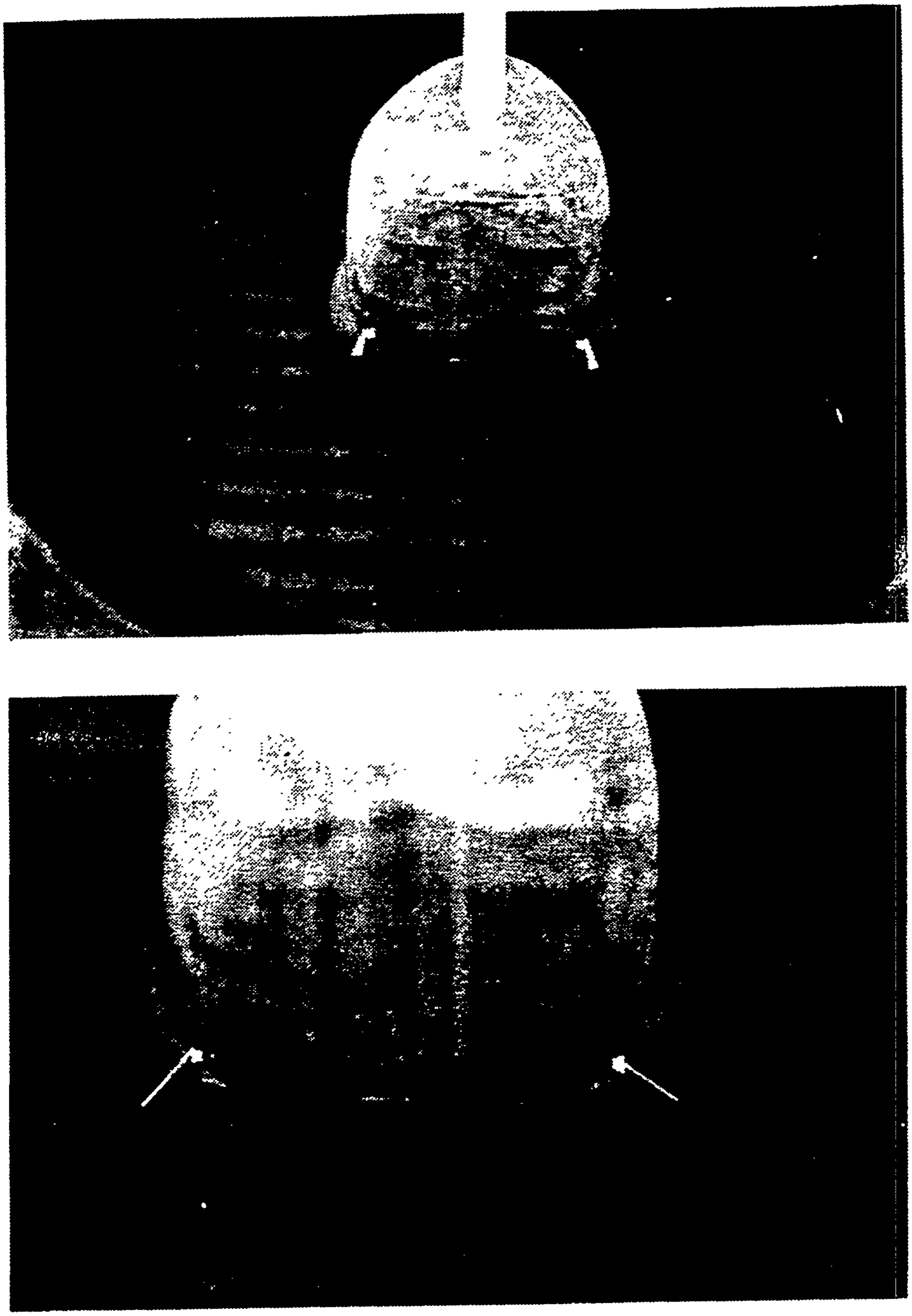


Figure 11. Vortex Generators on the C-5
(Local Fuselage Diameter is Approximately 15")

At M = .82 cruising speed at 40,000 ft, the dynamic pressure is approximately 200 psf. A vortex generator with 2 ft^2 area operating at 30° effective angle of attack would be subject to an aerodynamic force of approximately 100 pounds (440 N). Attachment of vortex generators to the existing fuselage skin and frame, by means of bolts and doubler plates, would not present any problems. If the vortex generators were made of fiberglass or aluminum, then a 1/2 inch thick, 2 ft^2 plate would weigh about 15 lbs. With attachments, the vortex assembly weight should not exceed 25 lbs, or 50 lbs per aircraft of the 747, C-5 class. Vortex generators could also be fabricated out of composite materials, but this would have to be determined in a preliminary design study.

Maintenance on the stationary plate-type vortex generators would be negligible. If variable pitch vortex generators were adopted to adjust the pitch angles with variations in flight conditions, then sensors, controls and actuators would have to be employed. Such a system would not be expensive or complicated but could require routine maintenance and functional checks. At present, only fixed pitch vortex generators are being considered.

Certification

The FAA certification will require flight test on an actual aircraft. If the vortex generator tests are added to an existing flight test program on the basis of non-interference with the prime objectives, then the cost of flight test will be insignificant. Flight test using a special 747 aircraft marked for such duty might take almost a month and cost $1 million. The latter figure is used in estimates of costs.

Maintenance and Life

The vortex generators have no moving parts and can be fabricated out of aluminum or fiberglass. Their maintenance is therefore essentially reduced to periodic cleaning and their service life is greater than that of the airframe.

Operational Problems

The vortex generators will be located in regions which are remote from aircraft control surfaces so that interference will be negligible. Because of their relatively small size (1% of length, 8% of local fuselage diameter) and location, vortex generators will not interfere with landing and take-off operations. In the case of the C-5, the vortex generators will be located ahead of the loading door. When the aircraft is lowered for loading the vortex generators can be made to rotate on a spring loaded pivot when contact with the runway is made. This will prevent any structural damage to the aircraft, or the vortex generator.

No significant operational problems are foreseen for the vortex generators.

Operating Cost Reductions

It is shown by Steiner[9] that a 5% reduction in drag results in a 3.6% reduction in operating costs of air transports. Here, in the case of the Boeing 747 the 1% reduction in overall aircraft drag would correspond to 0.72% reduction in operating costs. Current costs of operating a 747 transport are about $5,500/hr. Installation of the vortex generators would reduce costs by about $39.60/hr. It is stated in Reference 1 that Boeing 747 aircraft are operated approximately 3500 hours/year. If the vortex generators were used effectively only during 90% of that time at cruise conditions, then the annual reduction of operating costs would be about $125,000. This is probably a low figure because fuel prices appear to be rising and are likely to continue to do so in the future.

In Reference 10 the fuel consumption by US national airlines is given for the period 1975-1984, together with a trend line which can be extrapolated to 1986 to yield a figure of 60 x 10^9 gallons/year. If only half the fuel used is assumed to go into airliners with vortex generators and these are effective only during the time when 90% of the fuel is burned then the annual savings in fuel would be 270 x 10^6 gallons. At the present prices this is equivalent to about $270,000,000 or, in more concrete terms, the price of two new Boeing 747F transports.

Investment

Considerations will be limited here to Boeing 747 transports to which the wind tunnel data can be related directly. Under the assumption of 15 years of operation with annual savings of $130,000, the following figures can be calculated.

Discount Rate	Net Present Value
6%	$1,262,592
8%	$1,112,732
10%	$ 988,790

The following is a calculation of the return on investment for a range of installed costs of the vortex generators. These are the costs to air transport operators who would have the vortex generators installed on their aircraft.

Cost of Installation	Net Return
$500,000	25.1%
375,000	34.2%
250,000	51.8%

It appears that there should be a ready market for the devices even if they are sold for 100 times their total engineering, test, fabrication and installation costs.

MARKET

The vortex generator concept is most effective on transport aircraft with sharply upswept tails. Effectiveness is reduced as the upsweep and taper of the fuselage are reduced. In the civilian transport fleet, the following have been identified as the most likely candidates:

Boeing 747
Boeing 737
Boeing 727
Fokker F-27
CASA 212

The total fleet is estimated at approximately 4000 aircraft.

All aft loading military aircraft are particularly well suited for the use of vortex generators whose effectiveness for the C-5 has been shown to result in a 2% drag reduction. The following transports have been identified as potential candidates:

Lockheed C-5A, B
Lockheed C-141
Lockheed C-130 (All countries)

The total fleet is estimated at 2-3000 aircraft.

Even if only 10% of existing aircraft are retorfitted with vortex generators at an average price of $50,000/set the total market is estimated to be $300-350 x 10^6. In addition, new aircraft coming off the assembly lines could have the vortex generators attached as original equipment.

DISCUSSION

The concept of employing a small number of large vortex generators to influence both the inviscid flow field and a retarded boundary layer differs fundamentally from the conventional small scale devices which operate on the boundary layer alone. In the applications to transport aircraft fuselages, the tangential component of the vortex flow is used to counter the inflow towards the plane of symmetry while the strong axial flow energizes the boundary layer. Such strong interactions of an externally generated vortex with inviscid and viscous components of flow over aft regions of a fuselage are presently beyond analytical methods in aerodynamics and it is necessary to perform wind tunnel tests. Order of magnitude estimates and references to analogous flow situations were required to predict the size, configuration, pitch angles and locations of the vortex generators. Some preliminary tests of a Lockheed C-141 fuselage in the very small Cal State University Fullerton wind tunnel with very bad flow conditions were expected to guide the preliminary design of the current effort but careful analysis of the tunnel flow and balance system indicated that the University facility was of no value even in prediction of trends. Demonstration of the validity of the concept required a test of large models in a large wind tunnel with an established reputation. The tests were designed for the California Institute of Technology 10 ft tunnel and the model size was determined by the requirement that the region in which the vortex generators were located had to have a fully developed turbulent boundary layer. This was achieved with models of approximately 1:17 scale and the Reynolds number referred to length was approximately 10^7. Full scale Reynolds number is approximately 25×10^7 but the model test Reynolds number is high enough to ensure that the basic flows and their modifications corresponded closely with each other.

The usual pressures of budgets and schedules limited the number of configurations, attitudes and locations which could be tested. However, the results indicate that the effects are not very sensitive to variations of the above parameters so that it is very likely that the results are fairly close to the absolute optimum which can be achieved. The final optimization can probably be realized in full scale flight test for the certification of the devices.

The cost estimates are approximate since a detailed design, fabrication and installation study could not be performed within the scope of the program. It appears that the $2000 contingency added to the best estimate of $3000 for the total installed cost should be adequate for any unforeseen circumstances. Even if the cost was doubled, it would still be insignificant in relation to the economics of operation which could be realized through the use of vortex generators. The greatest problem in commercial deployment of the concept is the cost of the flight test program which is necessary for FAA certification.

CONCLUSIONS

The concept of attaching relatively large vortex generators on fuselages of transport aircraft to influence both the inviscid flow and the boundary layer was validated in extensive wind tunnel tests of models of Boeing 747 and Lockheed C-5 fuselages. Total aircraft drag reductions of 1% for the former and 2% for the latter can be realized through the use of simple stationary devices whose installed cost is estimated to be less than 5% of the reduction in the operating costs of a Boeing 747 for the first month of utilization. All aft loading military transports and most of the civilian airliners are seen as potential candidates for the installation of vortex generators.

If the vortex generators were deployed on transport aircraft at a cost of $250,000, then a 15 year lift of aircraft savings in fuel consumption would represent a return of over 50%. In view of the estimated $5,000 cost for engineering tests, fabrication, and installation, the potential sale price of $250,000 is extremely attractive. This appears to be a rare situation in which a device can be sold at an enormous profit and still represent an economically attractive acquisition to the purchaser. In principle, the concept should be irresistible to investors, aircraft component manufacturers, and aircraft transport fleet operators.

REFERENCES

1. Nicolai, L. M., Fundamentals of Aircraft Design, University of Dayton, Dayton, OH, 1975.

2. Pearcey, H. H., "Shock Induced Separation and its Prevention by Design and Boundary Layer Control." In Lachmann, G. V., Ed., Boundary Layer and Flow Control - Its Principles and Applications, Pergamon Press, Oxford, 1961.

3. Anon. "McDonnell Douglas Delivering MD-80's with Redesigned Tail Cones," Aviation Week and Space Technology, Vol., 127, No. 5, 3 August 1987.

4. Torenbeek, E., Synthesis of Subsonic Airplane Design, Delft University Press, 1982.

5. Wortman, A. and Franks, W. J., "Parametric Studies of Separating Turbulent Boundary Layer Flows," Presented at the NATO-AGARD Conference on Fluid Dynamics of Aircraft Stalling, April 1972, Lisbon, Portugal. Published in AGARD-CPP-102.

6. Schlichting, H., Boundary Layer Theory, Seventh Ed., McGraw-Hill, New York, 1979.

7. Wortman, A., "Correlation of Vortex Flows in Test Facilities with Full Scale Flow Phenomena," Report AFWAL-TR-80 3113, Prepared under contract by WARS Inc., as Report WARS-AF-80-05-01, Sept. 1980.

8. Jones, W. P., "Research on Unsteady Flow," MIT 1961, Minta Martin Lecture.

9. Steiner, J. E., "The Timing of Technology for Commercial Transport Aircraft," AIAA Astronautics and Aeronautics, October 1977, pp. 42-55.

10. Anon., "Decreasing Jet Fuel Price Trend Forecast to Reverse in 1987-1988," Aviation Week and Space Technology, Vol. 122, No. 11, 18 March 1985, pp. 222-224.

APPENDIX A

MODELS, CONTROLS AND ACTUATORS

The models built for this project were of Boeing 747 and Lockheed C-5A because of a decision to obtain data for representative large civilian and military transport aircraft. Size of the models was limited by tunnel blockage considerations. As a result of a decision to limit blockage to about 2% a scale of approximately 1:17 was selected and the fuselage lengths were approximately 13 ft (4 m). Empennages were attached to both fuselages, although in the case of the C-5A with its T-Tail configuration the justification was on esthetic rather than aerodynamic grounds. Wings were not attached to the fuselages which were faired into smooth contours at the locations of the wing roots.

The very large size of the models and the requirements of structural stiffness presented unusual construction problems. After several preliminary studies it was decided to fabricate the models out of wood with an internal steel channel beam to provide bending stiffness and base for supports. A layer construction was selected with layers of clear pine shaped approximately to the horizontal external contours of the fuselage being stacked vertically until a rough outline of the fuselage was obtained. Details of the construction are shown in Figure A-1. The steel backbone for the B-747 is also shown. The rough contours of the fuselages were sanded until cross sections were matched at a large number of longitudinal stations and the lines between the stations were smooth. After the final filling and sanding the models were stained and the empennages were attached. The completed models are shown in Figure A-2 with some of the personnel to indicate the scale involved.

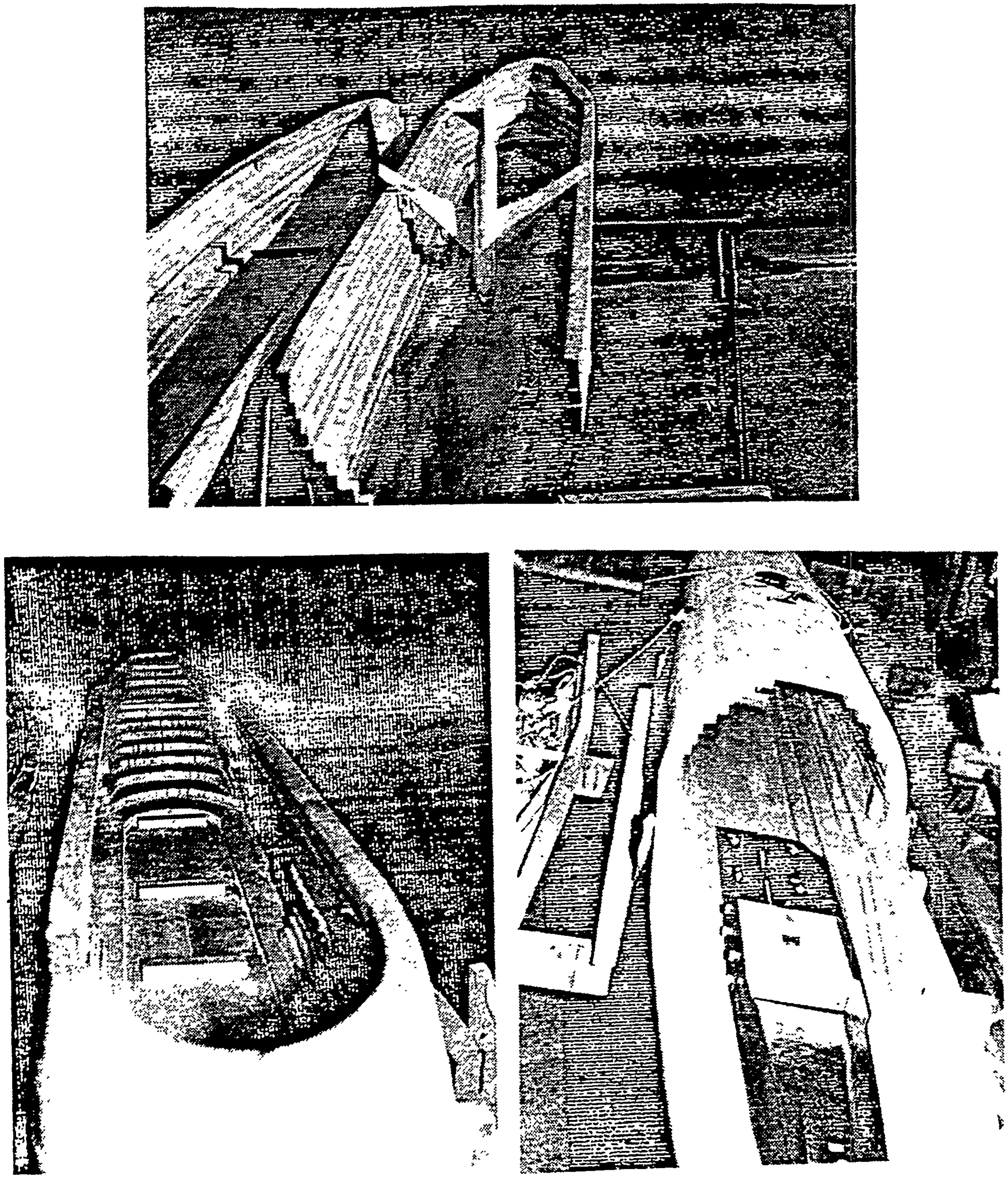
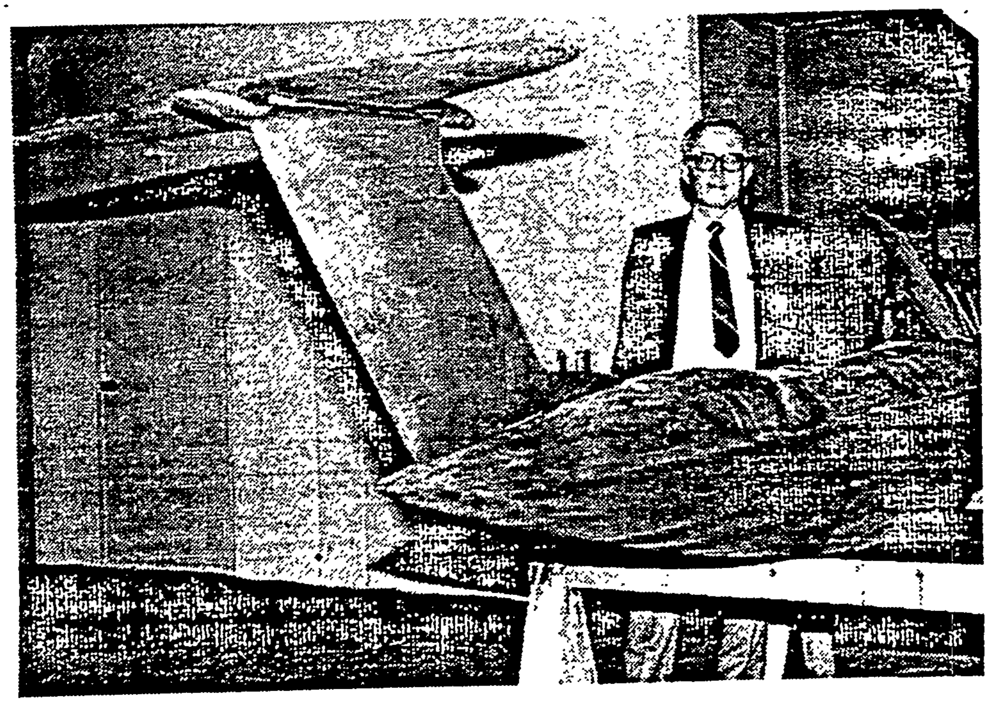


Figure A-1. Construction of the Fuselages
(Also shown is the steel backbone for the B-747
at lower right. Maximum widths are about 18".)



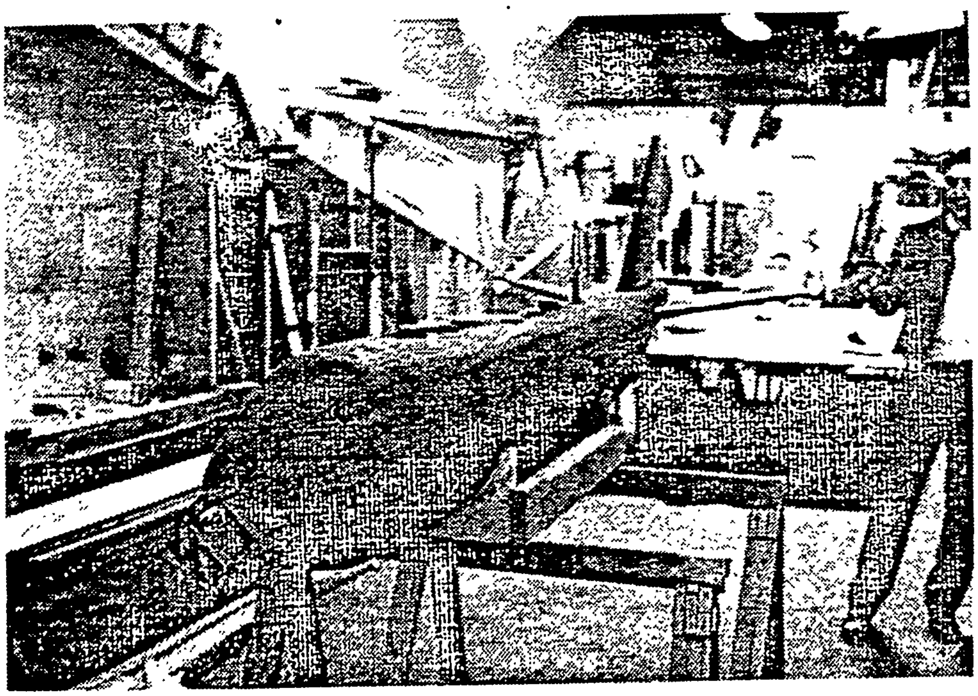


Figure A-2. Completed Models
(Scale may be gaged from the personnel
near the models)

Vortex Generators

Vortex generators were located in a region of the lower portion of the fuselage near the transition from the main fuselage to the upswept tail section. Because of stringent cost and scheduling considerations only six locations on each side of the fuselage were used. The complex three-dimensional flows in the regions of interest preclude predictions of optimum sites and best engineering judgement was used to fix the sites and vortex generator base pitch angles. Locations of vortex generators for the B-747 are shown in Figure A-3A and those for the C-5A are shown in Figure A-3B. Inserts are used in place of the vortex generators to indicate the locations and orientation of the vortex generators' axes of rotation.

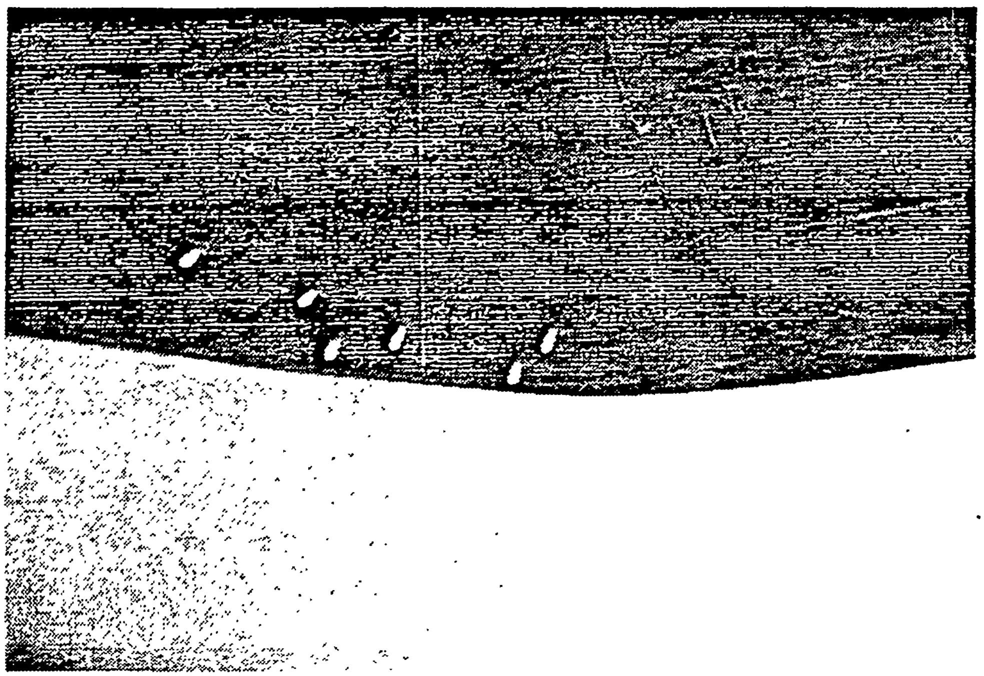
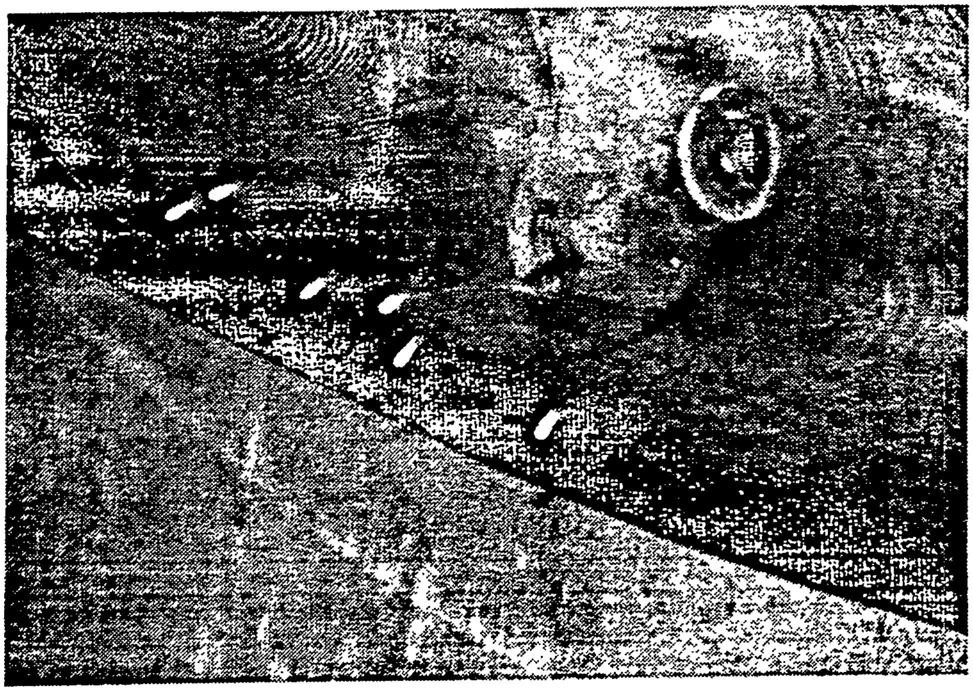


Figure A-3A. Locations of the Vortex Generators for the B-747 (Fuselage depth at this location is about 15")



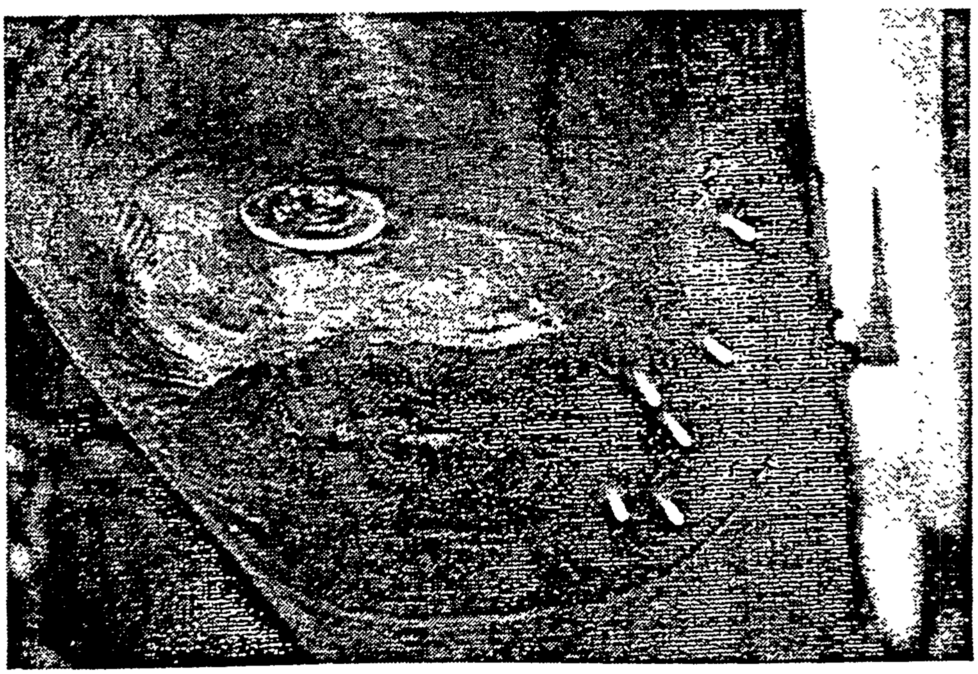


Figure A-3A. Locations of the Vortex Generators for the B-747 (Continued)

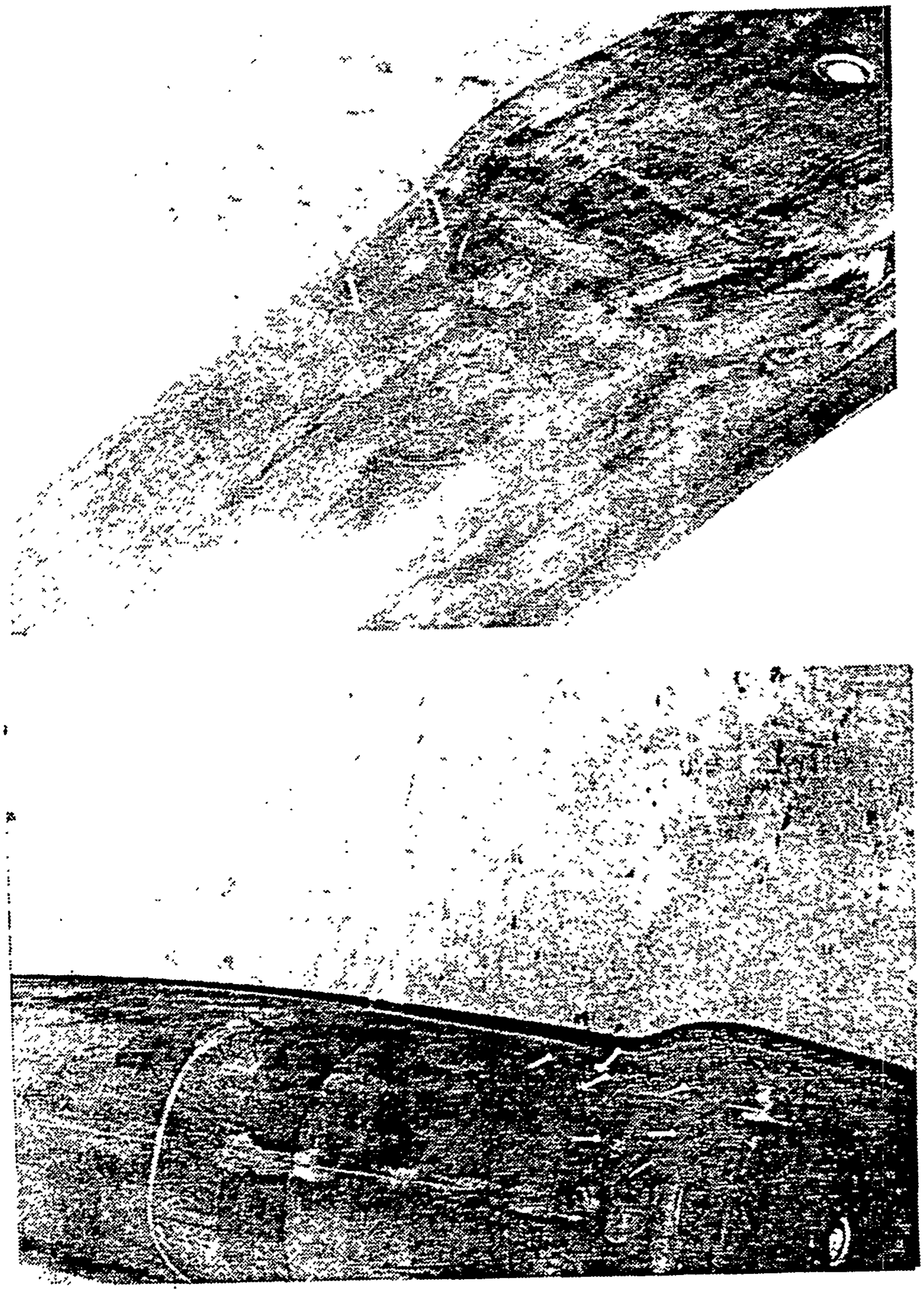


Figure A-3B. Locations of the Vortex Generators on the C-5A
(Fuselage bottom near the upsweep of the tail.
Fuselage width here is about 16".)

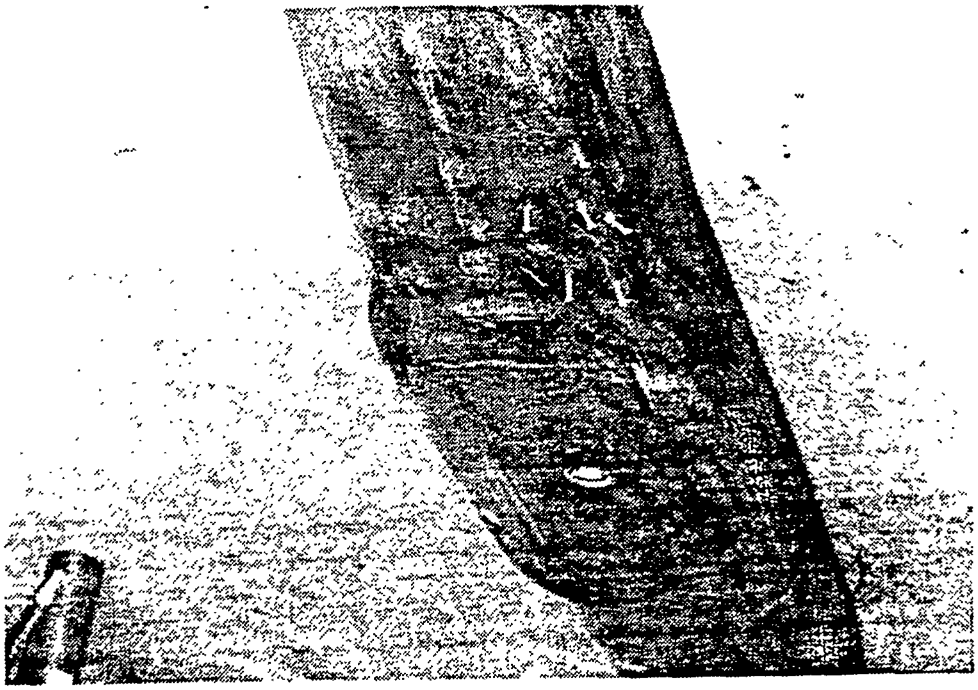


Figure A-3B. Locations of the Vortex Generators on the C-5A - View Forward (Continued)

Three vortex generator configurations, each in three different sizes were fabricated out of brass sheet 0.060" thick (1.5 mm). No attempt was made to sharpen the leading and trailing edges. Representative examples of each configuration in small, medium, and large sizes are shown in Figure A-4.

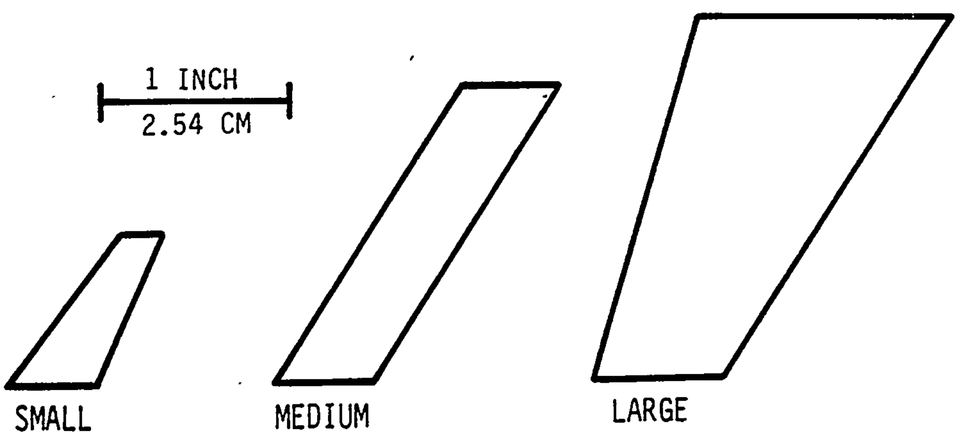


Figure A-4. Representative Vortex Generators

Representative examples of vortex generator installations on the B-747 and C-5A models are shown in Figures A-5A and A-5B respectively.

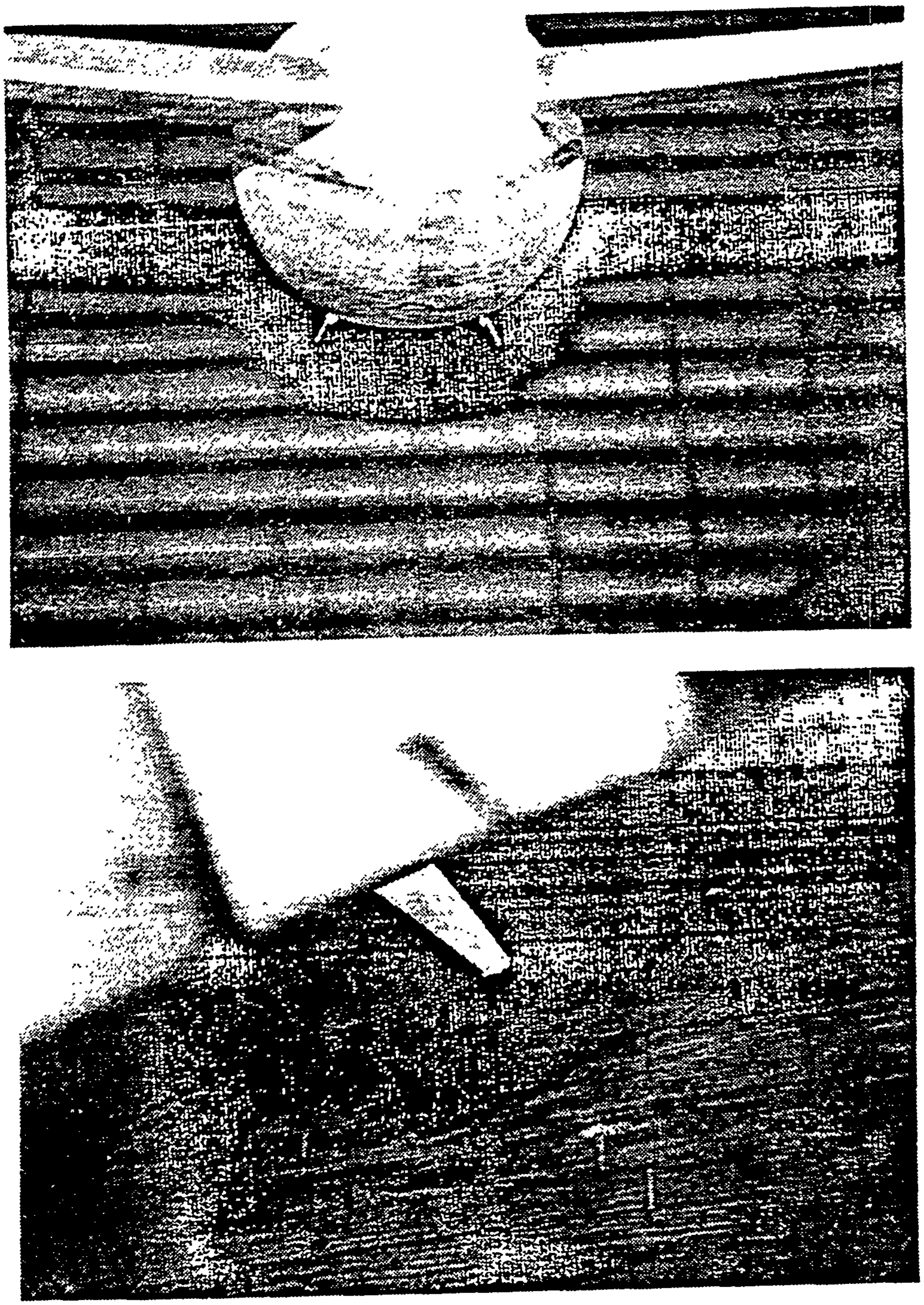
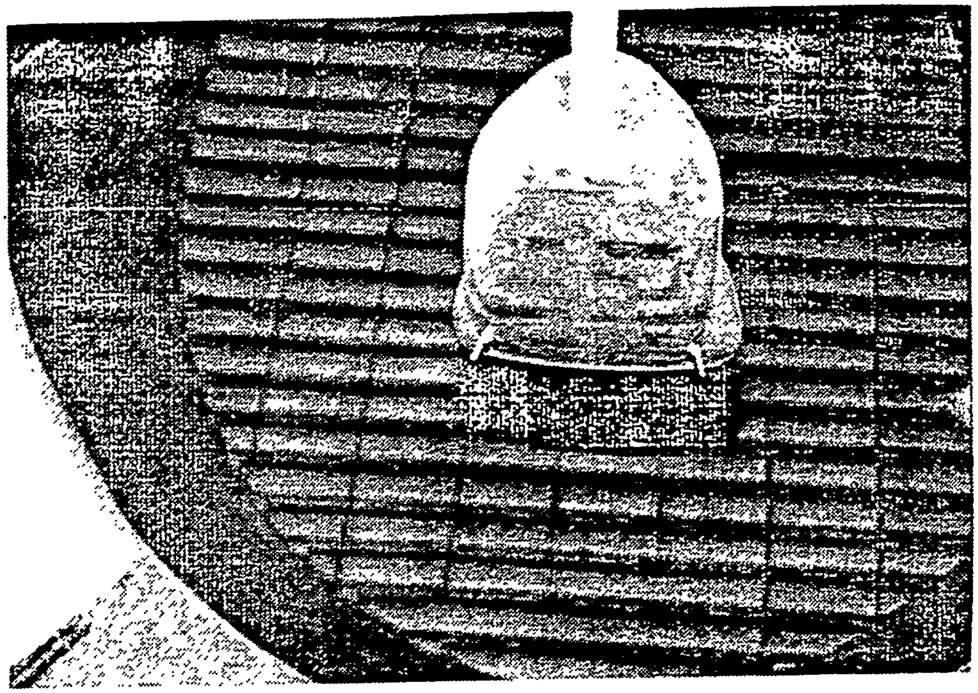


Figure A-5A. Vortex Generators on the B-747
(Vortex generator is 1.5")



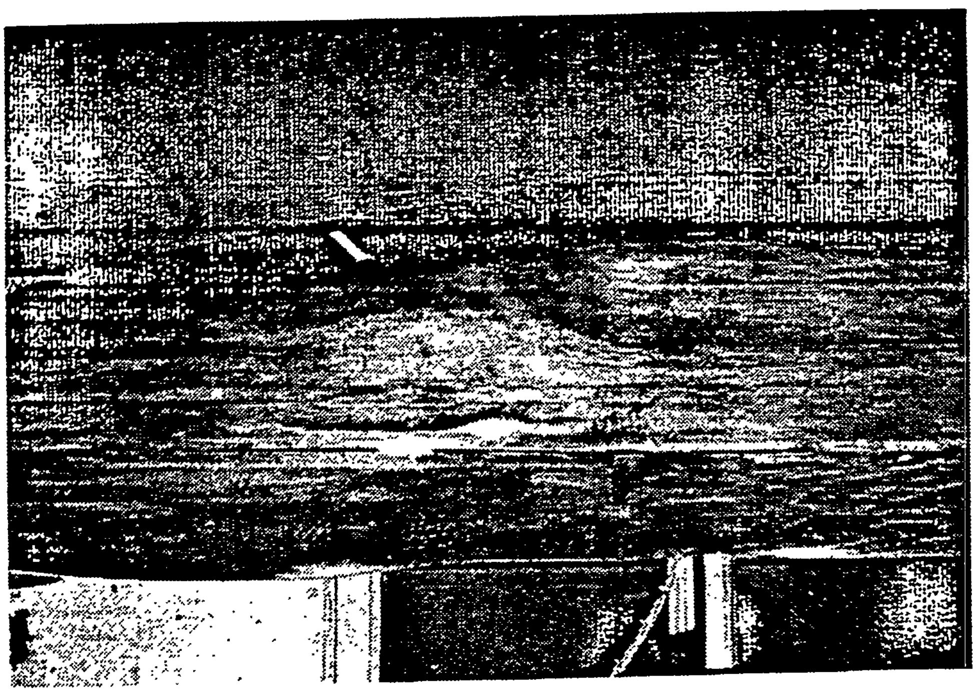


Figure A-5B. Vortex Generators on the C-5A (Bottom model is inverted for servicing. Vortex generator span is 3/4")

Controls and Actuators

The pitch angles of the vortex generators were controlled by a Futaba model airplane digital proportional radio transmitter-receiver set operating Futaba actuators which in turn rotated the vortex generators by means of rods and bell-cranks. All mechanisms were in a removable section of the fuselage so that adjustments and repairs could be made easily without interfering with the basic model in the wind tunnel support strut. The B-747 removable section and the actuating mechanisms are shown in Figure A-6.

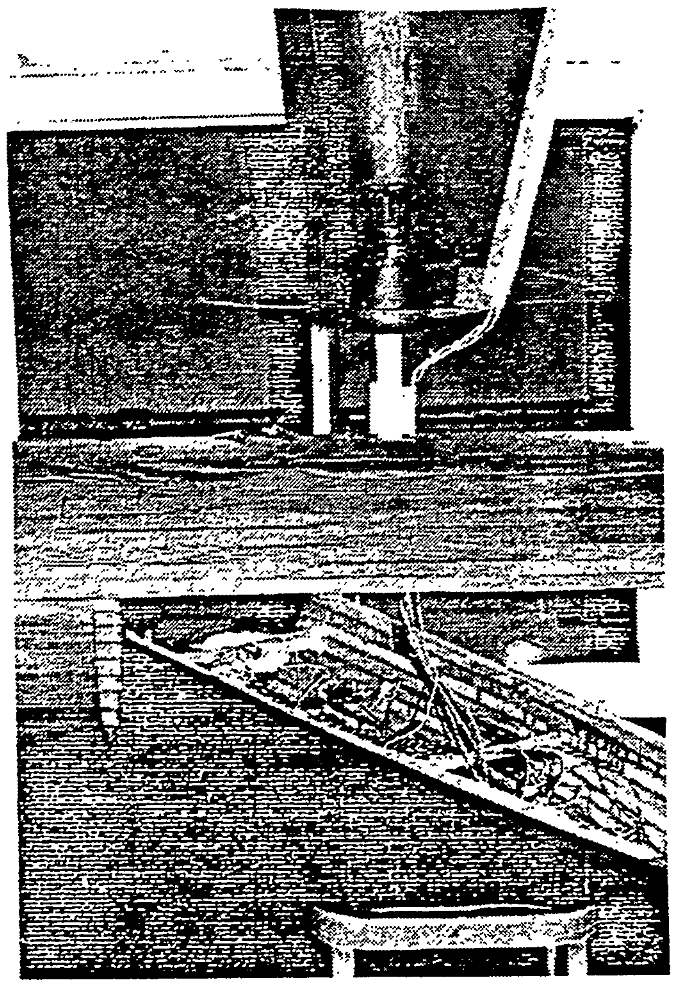


Figure A-6. Removable Section and Actuating Mechanisms

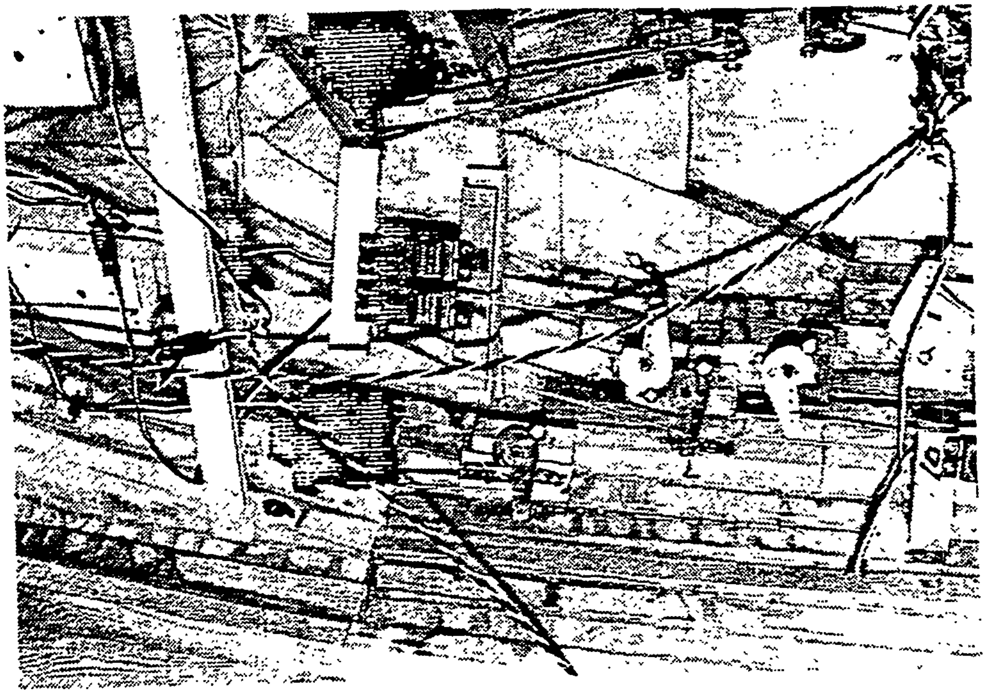


Figure A-6. Removable Section and Actuating Mechanisms (Continued). Fuselage width is 16".

During each run of a particular vortex generator set in a given location, the pitch angles were controlled remotely by the radio transmitter which was outside the tunnel. Pitch angles in increments of 25% of the full scale of the radio controller were used for most runs, with finer increments when significant drag reductions were noted.

APPENDIX B

MARKETING OF THE CONCEPT

The plan for commercial deployment of the vortex generators is to license the devices with royalty fees for each installation. Further involvement with the concept will be limited to consulting on wind tunnel tests of other aircraft models and certification flight testing data analysis.

The following efforts have been made so far to transition the concept to flight hardware:

a) Discussions were held with Aero Union in Chico, California to estimate the costs of engineering, fabrication and installation of vortex generators on commercial transports. Aero Union has undertaken to perform all these functions and to use their position as Class I supplier to Boeing to promote the idea there. Involvement of Aero Union in selling the idea to Boeing is very important because their subcontracting arrangements with Boeing make all their hardware automatically certificated.

b) The DOE Commercialization Planning Workshop at Battelle Institute in Seattle was attended to develop ideas for commercialization of the concept.

c) A copy of the presentation of vortex generator performance was given to D. Mitchell for transmittal to Boeing management.

d) Filing for a patent was initiated with J. Kirk.

The following are planned for the immediate future:

a) Presentations will be made to the Department of Defense with the aim of deploying the concept on military transport aircraft. DOE contacts at DOD will be used to get appropriate appointments.

b) Presentations will be made to Federal Express to either deploy the vortex generators on their aircraft, or to sell them the whole concept.

c) Contacts at Boeing will be followed up to ensure that the idea is given proper consideration.

d) Contacts will be established at CASA (Spain) to determine whether vortex generators would be of interest on the Model 212 aircraft.

e) Contacts will be made with Indonesia with the aim of selling the vortex generators for use on the CASA-Nurtanic aircraft.

Marketing efforts will continue at maximum effort until 31 January 1988. After that, the efforts will continue at greatly reduced levels.

APPENDIX C

WIND TUNNEL DATA

Notes

The aerodynamic data are given in "counts" which correspond to the weights on the wind tunnel balances and are approximately equal to grams. The lift figures are to be read directly and drag is the given number plus 1000 which is due to the added weight labeled DPAN.

STA # - Location of vortex generators given in Appendix A.

VG # - Vortex generator configurations given in Appendix A

Size - S - Small
M - Medium
L - Large

VG% - Percentage of full rotation of the vortex generator

D - Drag. Actual value is D + 1000

DPAN - Added weight on the balance. DPAN = 50 = 1000 counts

L - Lift in counts

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
BASELINE			1	0	1234	50	-72
1	1	S	2	0	1302	50	-71
				25	1330		-68
				50	1281		-70
				75	1289		-73
				100	1334		-72
1	1	M	3	0	1286	50	-72
				25	1258		-73
				50	1244		-73
				75	1246		-76
				100	1250		-80
1	1	L	4	0	1230	50	-72
				25	1240		-70
				50	1228		-79
				75	1227		-79
				100	1229		-84

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
1	2	S	5	0	1271	50	-73
				25	1214		-74
				50	1193		-73
				75	1219		-75
				100	1234		-73
1	2	M	6	0	1208	50	-72
				25	1201		-72
				50	1206		-77
				75	1217		-76
				100	1219		-81
1	2	L	7	0	1212	50	-69
				25	1218		-70
				50	1217		-68
				75	1227		-69
				100	1230		-74

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
1	3	S	8	0	1208	50	-71
				25	1210		-74
				50	1201		-73
				75	1206		-74
				100	1211		-73
1	3	M	9	0	1224	50	-63
				25	1213		-72
				50	1211		-74
				75	1214		-76
				100	1223		-78
1	3	L	10	0	1169	50	-59
				25	1189		-71
				50	1197		-74
				75	1209		-73
				100	1232		-74

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
3	2	S	11	0	1198	50	-67
				25	1196		-77
				50	1205		-78
				75	1205		-78
				100	1206		-76
3	2	M	12	0	1215	50	-69
				25	1221		-70
				50	1220		-71
				75	1225		-73
				100	1223		-72
3	2	L	13	0	1211	50	-68
				25	1208		-73
				50	1215		-69
				75	1214		-74
				100	1224		-76

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
3	3	S	14	0	1221	50	-69
				25	1217		-75
				50	1207		-76
				75	1203		-79
				100	1212		-79
3	3	M	15	0	1206	50	-70
				25	1207		-73
				50	1207		-77
				75	1216		-78
				100	1221		-79
3	3	L	16	0	1215	50	-63
				25	1216		-70
				50	1211		-72
				75	1219		-77
				100	1239		-83

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
4	2	S	18	0	1192	50	-68
				25	1194		-74
				50	1200		-76
				75	1214		-71
				100	1198		-76
4	2	M	19	0	1229	50	-58
				25	1228		-66
				50	1225		-75
				75	1223		-73
				100	1213		-72
4	2	L	20	0	1189	50	-60
				25	1217		-71
				50	1211		-75
				75	1212		-76
				100	1219		-75

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
4	3	S	21	0	1213	50	-72
				25	1213		-74
				50	1208		-73
				75	1212		-72
				100	1205		-74
4	3	M	22	0	1186	50	-72
				25	1196		-72
				50	1204		-72
				75	1204		-76
				100	1214		-76
4	3	L	23	0	1229	50	-64
				25	1225		-72
				50	1211		-75
				75	1207		-77
				100	1209		-78

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
5	3	S	26	0	1203	50	-73
				25	1214		-76
				50	1210		-78
				75	1209		-74
				100	1222		-78
5	3	M	27	0	1204	50	-72
				25	1211		-75
				50	1209		-77
				75	1201		-78
				100	1218		-82
5	3	L	28	0	1208	50	-71
				25	1211		-65
				50	1201		-76
				75	1202		-78
				100	1223		-77

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	2	S	17	0	1195	50	-77
				25	1195		-78
				50	1196		-79
				75	1206		-81
				100	1205		-82
6	2	M	24	0	1221	50	-58
				25	1229		-71
				50	1223		-72
				75	1214		-76
				100	1223		-77
6	2	L	25	0	1232	50	-56
				25	1220		-70
				50	1224		-73
				75	1223		-76
				100	1223		-76

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
2	1	S	29	0	1185	50	-67
				25	1188		-70
				50	1190		-74
				75	1192		-74
				100	1193		-72
2	1	M	30	0	1188	50	-70
				25	1199		-74
				50	1200		-71
				75	1212		-74
				100	1227		-75
2	1	L	31	0	1209	50	-67
				25	1201		-77
				50	1197		-78
				75	1208		-79
				100	1221		-77

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
2	2	S	32	0	1166	50	-63
				25	1190		-72
				50	1202		-75
				75	1195		-70
				100	1200		-75
2	2	M	33	0	1197	50	-73
				25	1197		-77
				50	1203		-77
				75	1202		-77
				100	1212		-80
2	2	L	34	0	1191	50	-68
				25	1209		-70
				50	1215		-71
				75	1207		-75
				100	1223		-73

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
2	3	S	35	0	1185	50	-69
				25	1196		-71
				50	1201		-74
				75	1197		-73
				100	1179		-74
2	3	M	36	0	1223	50	-64
				25	1227		-74
				50	1226		-73
				75	1224		-76
				100	1223		-74
2	3	L	37	0	1212	50	-65
				25	1217		-79
				50	1218		-79
				75	1235		-80
				100	1247		-78

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
3	1	S	38	0	1208	50	-68
				25	1217		-75
				50	1200		-76
				75	1201		-74
				100	1204		-72
3	1	M	39	0	1219	50	-71
				25	1205		-72
				50	1200		-78
				75	1195		-78
				100	1210		-81
3	1	L	40	0	1215	50	-65
				25	1218		-70
				50	1211		-73
				75	1208		-74
				100	1217		-76

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
4	1	S	41	0	1188	50	-74
				25	1182		-74
				50	1190		-75
				75	1203		-71
				100	1196		-71
4	1	M	42	0	1191	50	-74
				25	1196		-78
				50	1193		-75
				75	1189		-77
				100	1209		-78
4.	1	L	43	0	1198	50	-67
				25	1210		-68
				50	1214		-71
				75	1195		-83
				100	1208		-74

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
5	1	S	44	0	1185	50	-71
				25	1190		-72
				50	1195		-75
				75	1199		-72
				100	1196		-73
5	1	M	45	0	1223	50	-80
				25	1232		-83
				50	1207		-85
				75	1209		-86
				100	1210		-89
5	1	L	46	0	1226	50	-76
				25	1209		-82
				50	1211		-85
				75	1208		-88
				100	1211		-89

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	1	S	47	0	1216	50	-74
				25	1211		-80
				50	1177		-82
				75	1187		-81
				100	1185		-80
6	1	S	48	0	1214	50	-78
				25	1209		-80
NO SHUT DOWN				50	1212		-84
				75	1185		-85
				100	1200		-82
6	1	S	49	0	1209	50	-79
				25	1206		-84
BALANCE ZERO RETURNS				50	1205		-80
POST RUNS				75	1206		-83
				100	1201		-87

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	1	S	49	0	1202	50	-86
				25	1200		-86
RE-RUN OF 47 & 48				50	1200		-87
PORT SIDE - VG BINDING				75	1214		-85
				100	1200		-88
6	1	M	50	0	1218	50	-74
				25	1212		-78
				50	1204		-82
				75	1200		-87
				100	1206		-84
6	1	L	51	0	1210	50	-80
				25	1220		-86
				50	1231		-88
				75	1223		-88
				100	1228		-91

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	3	S	52	0	1208	50	-83
				25	1204		-88
				50	1187		-86
				75	1183		-88
				100	1187		-87
6	3	M	53	0	1215	50	-78
				25	1208		-78
				50	1200		-86
				75	1206		-81
				100	1219		-84
6	3	L	54	0	1210	50	-73
				25	1202		-80
				50	1203		-85
				75	1235		-85
				100	1234		-85

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
5	2	S	55	0	1211	50	-76
				25	1196		-76
				50	1194		-83
				75	1191		-83
				100	1197		-80
5	2	M	56	0	1215	50	-74
				25	1215		-80
				50	1206		-82
				75	1223		-77
				100	1204		-82
5	2	L	57	0	1207	50	-75
				25	1207		-77
				50	1210		-80
				75	1212		-81
				100	1211		-83

747 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
2	2	S	58	0	1188	50	-80
				25	1191		-78
				50	1181		-76
1	3	L	59	0	1190	50	-70
				25	1196		-76
				50	1198		-70
1	3	L	60	0	1223	50	-79
2	2	S	60	0	1223	50	-79
1	3	L	61	0	1228	50	-80
2	2	S		0	1195		-77
				25	1204		-78
				50	1213		-78
				75	1200		-81
				100	1214		-80
2	2	S	62	0	1200	50	-85
				25	1195		-82
				50	1189		-84
				75	1185		-87
				100	1206		-82
1	3	L	64	0	1219	50	-77
				25	1185		-83
				50	1173		-88
				75	1214		-90
				100	1226		-88
BASELINE			65	0	1213	50	-81

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
BASELINE			66	0	1812	0	145
1	1	S	67	0	1817	0	157
				25	1834		154
				50	1846		159
				75	1851		157
				100	1858		153
2	2	S	68	0	1783	0	157
				25	1816		160
				50	1825		155
				75	1832		154
				100	1838		154
2	3	S	69	0	1802	0	151
				25	1820		152
				50	1827		149
				75	1838		152
				100	1843		152
2	3	M	70	0	1809	0	161
				25	1829		158
				50	1830		157
				75	1835		152
				100	1847		153
3	1	S	71	0	1778	0	155
				25	1791		162
				50	1802		159
				75	1814		165
				100	1824		155

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	1	S	72	0	1801	0	155
				25	1807		154
				50	1811		155
				75	1817		158
				100	1830		153
6	1	M	73	0	1808	0	171
				25	1828		170
				50	1839		157
				75	1848		153
				100	1859		150
6	2	S	74	0	1813	0	161
				25	1826		164
				50	1832		155
				75	1839		157
				100	1845		150
6	2	M	75	0	1791	0	164
				25	1815		161
				50	1819		157
				75	1825		155
				100	1827		156
6	2	L	76	0	1804	0	168
				25	1820		163
				50	1835		163
				75	1842		163
				100	1844		159

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
6	3	S	77	0	1799	0	163
				25	1803		162
				50	1819		157
				75	1829		157
				100	1832		155
6	3	M	78	0	1804	0	170
				25	1813		165
				50	1823		166
				75	1825		157
				100	1841		155
6	3	1	78	0	1814	0	176
				25	1821		172
				50	1822		164
				75	1833		155
				100	1841		153

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
1	1	L	80	0	1766	0	177
				25	1771		170
				50	1779		163
				75	1784		160
				100	1795		161
1	1	L	81	0	1768	0	176
				25	1776		169
REPEAT OF 80				50	1784		162
				75	1795		162
				100	1802		156
1	3	S	82	0	1761	0	172
				25	1770		163
				50	1768		164
				75	1776		163
				100	1770		165
1	3	M	83	0	1737	0	168
				25	1742		164
				50	1753		163
				75	1765		159
				100	1781		157
1	3	L	84	0	1735	0	165
				25	1762		159
				50	1787		153
				75	1794		159
				100	1804		154

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
3	3	S	85	0	1755	0	164
				25	1761		158
				50	1777		156
				75	1783		153
				100	1776		157
3	3	M	86	0	1749	0	164
				25	1760		155
				50	1768		159
				75	1780		153
				100	1797		151
3	3	L	87	0	1743	0	157
				25	1756		161
				50	1771		153
				75	1773		151
				100	1785		155

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
4	3	L	88	0	1760	0	173
				25	1780		176
				50	1787		166
				75	1801		161
				100	1808		159
4	2	M	89	0	1735	0	165
				25	1749		161
				50	1776		161
				75	1779		157
				100	1775		158
4	2	S	90	0	1760	0	167
				25	1760		170
				50	1766		167
				75	1762		164
				100	1769		158
4	2	L	91	0	1769	0	167
				25	1778		165

C5 INVERTED
TAIL/NO WINGS

STA#	VG#	SIZE	RUN	VG%	D	DPAN	L
5	3	S	92	0	1738	0	160
				25	1758		164
				50	1779		160
				75	1766		162
				100	1779		163
5	3	M	93	0	1736	0	158
				25	1748		157
				50	1781		162
				75	1781		159
				100	1792		158
5	3	L	94	0	1744	0	169
				25	1774		158
				50	1786		161
				75	1807		161
				100	1811		155
5	2	S	95	0	1743	0	162
				25	1750		161
				50	1772		157
				75	1765		160
				100	1774		161
5	2	M	96	0	1710	0	156
				25	1736		159
				50	1759		163
				75	1771		158
				100	1767		155
5	2	L	97	0	1733	0	165
				25	1751		161
				50	1754		165
				75	1770		160
				100	1777		163
5	1	M	98	0	1734	0	170
				25	1753		167
				50	1759		165
				7?	1778		159
				100	1787		161

DR. A. WORTMAN

RESUME

Education

PhD in Energy and Kinetics, Engineering, UCLA (1969)
MS in Aerosciences, Engineering, UC Berkeley (1958)
BS in Mechanical Engineering, UC Berkeley (1956)

Experience

Extensive experience as technical director, consultant, research engineer, professor and manager of a broad range of research and development projects in airborne and underwater weapons, propulsion and power generation. Technical direction of Minuteman and Titan missiles ascent and silo heat protection systems. Consultant in aero-propulsion and performance of stand-off and defensive weapons, stealth cruise missiles, harassment and target drones, reconnaissance and special mission RPV's. Extensive laboratory and field testing experience in aero-hydrodynamics, weapons effects, shock and detonation phenomena, special vehicles, engines, and fluid flow machinery. Specific areas:

Government Representation - Designated expert and consultant on: DOE-SERI OC-OTEC and oscillating flow wave turbines, DOE fluidized bed combustors, DOC-NBS energy related inventions. Member of the State of California Air Resources Board.

Consulting - Aerospace engineering, weapon systems, oil platforms, turbine designs, energy transfer equipment and vehicle engineering.

Expert witness - numerous legal matters concerning engines, vehicles, aircraft, and energy projects.

Teaching - Taught university engineering courses.

Technical Direction - RPV and cruise missile aerodynamics and propulsion, torpedo hydrodynamics, propulsion and silencing, submarine launchways, underwater delivery vehicles and ASW concepts, OTEC turbine studies, and rescue vehicle development.

Technical Management - Projects in truck aerodynamics, detonation augmented turbines, hybrid vehicles, water tunnel tests, and transport aircraft drag, RPV concepts and flight test services.

Government Contacts

DARPA
NASA - HQ, ARC, LaRC, LeRC
USAF - AFOSR, WPAFB
USDOC - NBS
USDOE - HQ, SERI
USN - China Lake, CSC, NOSC, NUSC, ONR

Consultant

ASA - Expert Witness
Honeywell - Underwater weapons
Librascope - Hydrodynamics
Northrop - Torpedo design
TRW - Wave effects
SERI - OTEC, turbines
Vetco - Oil platforms

DR. A. WORTMAN

Honors and Appointments

Highest Scholarship and Highest Honors with BS
Highest graduate scholarships 1956-1958
Sigma XI, Pi Tau Sigma, Tau Beta Pi
Post Doctoral Scholar, UCLA 1970-1975
National Academy of Sciences Exchange Scholar 1971-1976
National Bureau of Standards Certificate of Appreciation
Member, State of California Air Resources Board 1983-

Publications

Book	- Introduction to Wind Turbine Engineering, Butterworth Publishers, Boston, 1983
Papers and Notes	- 48 in the open literature on hydrodynamics, aerodynamics, and heat transfer
Reports	- Over 650 on aerodynamics, vehicle designs, wind turbines, tunnel tests, and propulsion

Seminars

USAF, USN, NASA, IPPT
Fuel tank hydrodynamics, weapons blast effects, wing-vortex flows, viscous flows, advanced gas turbine concepts, applied mathematics

Outline of Experience in Research and Development

1958	Consultant to STL/TRW in gas dynamics and rarefied gas flows.
1959-1960	Research Assistant at the University of California, Berkeley in the gas dynamics and detonation research laboratory.
1960-1961	Research Engineer at UTC, United Aircraft engaged in theoretical and experimental studies of solid propellant rocket motors and nozzle heat transfer.
1961-1963	Member of the Technical Staff at STL/TRW engaged in theoretical and experimental studies of reentry vehicles, heating, and aerodynamics. Responsible for the technical direction of the aerothermodynamics of the Titan and Minuteman Weapon Systems. Main effort was directed at the development of the methods of analysis of complex aerothermodynamics problems of reentry vehicles and experimental studies of transient heat transfer during silo launches.
1964-1975	Head of Viscous Aerodynamics Task Force at Northrop Corporation, Aircraft Group. Directed the development of viscous aerodynamics computation capabilities. Devised techniques for simple, inexpensive, free-flight testing in hypersonic wind tunnels. Among other accomplishments were theoretical and experimental studies of the dynamics of gun blasts and the dynamics of high-speed projectiles in

	liquid-filled tanks. Patented aerothermodynamic device for measuring altitude, velocity, and attitude of reentry vehicles.
1969-1974	Postdoctoral Scholar in the University of California, Los Angeles, Energy and Kinetics Department. Engaged in fundamental studies of heat and mass transfer phenomena.
1971-1972	US Academy of Sciences Exchange Scholar in Poland. Fundamental studies of fluid mechanics and gas dynamics.
1975	Manager of Aerothermodynamics and Energetics at Science Applications Inc. Heat and mass transfer studies of reentry vehicles. Fluidized bed trans fer phenomena.
1975-1979	Consultant to Northrop Corporation, Ventura Division. Directed the Analytical studies of the aerodynamics of special mission airborne vehicles and developed computer codes for calculations of propulsion duct and exhaust plume flows for infrared signal studies. Developed, under contract, a computational procedure for predicting, by means of exact viscid-inviscid calculations, the performance of yawed axisymmetric vehicles.
1979-1981	Consultant to Librascope. Engaged in the development of advanced underwater weapons, decoys, and countermeasures. Projects included torpedo neutralization launchway hydrodynamics, under- water delivery vehicles, and ship defense systems.
1975-now	Technical Director of ISTAR Inc. and AWD Inc. Engaged in the analysis of development of special purpose underwater vehicles. Analysis of trans- ient flows in open cavities. Under Air Force contract developed fundamental criteria for the analysis of vortex flows on aircraft. Engaged by NBS to evaluate energy related concepts in fluid mechanics and thermodynamics. Under NBS contract, wrote Guidelines for Evaluating Wind Turbine Generating Systems. As consultant to SERI/DOE performed original analysis of wave motion energy oscillating flow chamber turbine gas dynamics and developed modelling criteria for low pressure OTEC turbines. Engaged in the development of a lightweight aerodynamic fairing for trucks under a DOE contract. Development of advanced gas turbine concepts under contracts from NASA.
1982-1987	Associate Professor of Mechanical Engineering at the California State University, Fullerton.
1983-	Member of the State of California Air Resources Board.

DR. ANDREW WORTMAN
PUBLICATIONS

1. Ambrosio, A., and Wortman, A., "Stagnation Point Shock Detachment Distance for Flow Around Spheres and Cylinders," American Rocket Society Journal, Vol. 32, No. 2, February 1962, p. 281.

2. Ambrosio, A., and Wortman, A., "Stagnation Point Shock Detachment Distance for Flow Around Spheres and Cylinders in Air," Journal of the Aeronautical Sciences, Vol. 29, No. 7, July 1962, p. 875.

3. Wortman, A., "Laminar Boundary Layer Heat Transfer in Shear Flows," presented at the 48th Bumblebee Aerodynamics Panel Meeting, Austin, Texas, September 1963. Paper in Conference Proceedings.

4. Wortman, A., "Comments on Simplified Solutions for Ablation in a Finite Slab," AIAA Journal, Vol. 4, No. 4, April 1966, p. 760.

5. Wortman, A., "Two Unconventional Methods of Testing in Hypersonic Wind Tunnels," IEEE Aerospace Systems Conference, Seattle, WA, July 1966, Conference Proceedings 205-207.

6. Wortman, A., "Aerodynamics of Randomly Tumbling Bodies," Journal of Spacecraft and Rockets, Vol. 6, No. 2, February 1969, pp. 205-207.

7. Wortman, A., "High Energy Recovery Pressure and Enthalpy Sensor," presented at the 3rd IEEE International Congress of Instrumentation in Aerospace Simulation Facilities, May 1969, New York. Paper in Conference Proceedings.

8. Wortman, A., "Reentry Vehicle Altitude Velocity Sensor," AIAA Paper No. 69-866, presented at the AIAA Guidance, Control, and Flight Mechanics Conference, August 1969, Princeton, New Jersey.

9. Wortman, A., and Mills, A. F., "Highly Accelerated Compressible Laminar Boundary Layer Flows with Mass Transfer," ASME Paper No. 70-HT/SpT-34, presented at the ASME 1970 Space Technology and Heat Transfer Conference, June 1970, Los Angeles. Published in the ASME Journal of Heat Transfer, Vol. 93, Ser. C., No. 3, August 1981, pp. 281-289.

10. Wortman, A., "Boundary Layers at Three-Dimensional Stagnation Points in High Speed Air Streams," AIAA Paper No. 70-809, presented at the AIAA Third Fluid and Plasma Dynamics Conference, July 1970, Los Angeles.

11. Wortman, A., "Foreign Gas Injection at General Three-Dimensional Stagnation Points," Presented at the Aerospace Corporation Workshop on Transpiration Cooling in Three- Dimensional Flow Fields, San Bernardino, January 1971. Figures for the presentation in the Proceedings of the Workshop, Aerospace Corp., Document No. SA-71-80036, edited by R. L. Strickler and F. L. Fernandez.

12. Wortman, A., Ziegler, H., and Soo-Hoo, G., "Convective Heat Transfer at General Three-Dimensional Stagnation Points," International Journal of Heat and Mass Transfer, Vol. 14, January 1971, pp. 149-152.

13. Wortman, A., "Three-Dimensional Stagnation Point Heat Transfer in Equilibrium Air Flows," AIAA Journal, Vol. 9, No. 5, May 1971, pp. 955-962.

14. Wortman, A., and Mills, A. F., "Mass Transfer Effectiveness at Three-Dimensional Stagnation Points," AIAA Journal, Vol. 9, No. 6, June 1971, pp. 1210-1212.

15. Wortman, A., and Mills, A. F., "Recovery Factors in Highly Accelerated Laminar Boundary Layer Flows," AIAA Journal, Vol. 9, No. 7, July 1971, pp. 1415-1417.

16. Wortman, A., and Franks, W. J., "Comments on the Method of Weighted Residuals Applied to Free Shear Layers," AIAA Journal, Vol. 9, No. 11, November 1971, pp. 2303-2304.

17. Wortman, A., and Mills, A. F., "Separating Self-Similar Laminar Boundary Layers," AIAA Journal, Vol. 9, No. 12, December 1971, pp. 2449-2451.

18. Wortman, A., Mills, A. F., and Soo-Hoo, G., "The Effect of Mass Transfer on Recovery Factors in Laminar Boundary Layer Flows," International Journal of Heat and Mass Transfer, Vol. 15, No. 3, March 1972, pp. 443-456.

19. Wortman, A., and Franks, W. J., "Parametric Studies of Separating Turbulent Boundary Layer Flows," presented at the NATO-AGARD Conference on Fluid Dynamics of Aircraft Stalling, 25-26 April 1972, Lisbon, Portugal. Published in AGARD-CPP-102.

20. Mills, A. F., and Wortman, A., "Two-Dimensional Stagnation Point Flows of Binary Mixtures," International Journal of Heat and Mass Transfer, Vol. 15, No. 5, May 1972, pp. 969-987.

21. Wortman, A., "Heat and Mass Transfer on Cones at Angles of Attack," AIAA Journal, Vol. 10, No. 5, June 1972, pp. 832-834.

22. Wortman, A., "Comments on Dynamics of an Explosive Reaction Center," AIAA Journal, Vol. 10, No. 6, June 1972, pp. 846-847.

23. Wortman, A., "Foreign Gas Injection into Three-Dimensional Stagnation Point Flow," AIAA Journal of Spacecraft, Vol. 9, No. 6, June 1972, pp. 428-434.

24. Wortman, A., "Non-Steady Flow at General Three-Dimensional Stagnation Points," presented at the 11th Yugoslav Conference of Rational and Applied Mechanics, 5-10 June 1972, Basko Polje, Yugoslavia.

25. Wortman, A., "Exact Solutions of Non-Steady Navier-Stokes Equations at General Three-Dimensional Stagnation Points," Mechanics Colloquium on "Numerical Methods of Solving Navier-Stokes Equations," Euromech 27, 16-20 August 1972, Jablonna, Poland.

26. Fiszdon, W., Walenta, Z., and Wortman, A., "An Experimental and Theoretical Study of the Distortion of Traveling Shock Wave by Wall Effects." Presented at the IUTAM 13th Congress, 21-26 August 1972, Moscow, USSR. Also, in the Archiwum Mechaniki Stonsowanej, Warszawa, Poland, Vol. 26, No. 3, March 1974, pp. 479-497.

27. Wortman, A., "Foreign Gas Injection at Windwardmost Meridians of Yawed Sharp Cones," AIAA Paper No. 73-764. Presented at the AIAA 8th Thermophysics Conference 16-18 July 1973, Palm Springs, California, AIAA Journal, Vol. 12, No. 6, June 1974, pp. 741-742.

28. Wortman, A., and Franks, W. J., "Reversed Boundary Layer Flows with Variable Fluid Properties." Presented in the Open Forum Session of the AIAA 8th Thermophysics Conference, 16-18 July 1973, Palm Springs, California. AIAA Journal, Vol. 12, No. 3, March 1974, pp. 406-408.

29. Wortman, A., and Mills, A. F., "Accelerating Compressible Laminar Boundary Layer Flows of Binary Gas Mixtures." Presented at the XIth Biennial Fluid Dynamics Symposium on Advanced Problems and Methods in Fluid Mechanics, 3-8 September 1973, Sopot-Kamienny Potok, Poland. Also, in Archiwum Mechaniki Stosowanej, Warszawa, Poland, Vol. 26, No. 3, March 1974, pp. 487-505.

30. Wortman, A., "Exact Solutions of Three-Dimensional Boundary Layer Equations Using Operator Techniques." Presented at the Conference on Three-Dimensional Boundary Layers and Boundary Regions, 28 January 1974, Old Dominion University (VARC), Virginia.

31. Wortman, A., "Comments on the Increase of Boundary Layer Heat Transfer by Mass Injection," AIAA Journal, Vol. 12, No. 4, April 1974, pp. 573-574.

32. Wortman, A., "Unsteady Flow Phenomena Causing Weapons Fire-Aircraft Engine Inlet Interference Problems-Theory and Experiments." Presented at the Symposium on Unsteady Aerodynamics, Tucson, Arizona, 17-20 March 1975. Paper in Conference Proceedings.

33. Wortman, A., "Three-Dimensional Turbulent Boundary Layer Calculations-Exact and Simplified Solutions," AIAA Paper No. 75-854. Presented at the AIAA 8th Fluid and Plasma Dynamics Conference, Hartford, Conn., 16-18 June 1975, p. 54.

34. Wortman, A., and Soo-Hoo, G., "Exact Operator Solutions of General Three-Dimensional Boundary Layer Flow Equations." AIAA Journal of Aircraft, Vol. 13, No. 8, Aug. 1976, pp. 590-596.

35. Wortman, A., "Comments on Controlling the Separation of Laminar Boundary Layers in Water: Heating and Suction," AIAA Journal of Hydronautics, Vol. 12, No. 2, April 1978, pp. 87-88.

36. Wortman, A., "Impact of Torpedoes on Nets," AIAA Journal of Hydronautics, Vol. 1 5, Nos. 1-4, Jan-Dec 1981, pp. 97-98.

37. Wortman, A., "Comments on Critical Field Length Calculations for Preliminary Design," AIAA Journal of Aircraft, Vol. 19, No. 3, March 1982, pp. 255-256.

DR. ANDREW WORTMAN
PUBLICATIONS

38. Wortman, A., "Performance of Underwater Vehicles Employing Lift to Reduce Drag," AIAA Journal, Vol. 20, No. 4, April 1982, pp. 564-566.

39. Wortman, A., "Testing of Unpowered Advanced Underwater Vehicles at Very High Reynolds Numbers," AIAA Journal of Aircraft, Vol. 19, No. 4, April 1982, pp. 339-340.

40. Wortman, A., "Comments on Rational Design of an Airfoil for a High Performance Jet Trainer," AIAA Journal of Aircraft, Vol. 19. No. 7, July 1982, pp. 607-608.

41. Wortman, A., "Comments on Dynamic Rotor Loads of a Wind Turbine via Hand Held Calculators." AIAA Journal of Energy, Vol. 6, No. 5, Sept-Oct 1982, p. 351

42. Wortman, A., "Optimum Performance of Propeller Wind Turbine Blades." AIAA Journal of Energy, Vol. 7, No. 1, Jan-Feb 1983, pp. 640-643.

43. Wortman, A., "Performance of Propeller Wind Turbines," AIAA Journal of Energy, Vol. 7, No. 6, Nov-Dec 1983, pp. 640-643.

44. Wortman, A., "On Reynolds Number Effects in Vortex Flow over Aircraft Wings," AIAA Paper No. AIAA-84-0137. Presented at the AIAA 22nd Aerospace Sciences Meeting, Jan 9-12, 1984, Reno, Nevada.

45. Wortman, A., "Detonation Wave Augmentation of Gas Turbines," AIAA Paper No. AIAA-84-1266. Presented at the AIAA/SAE/ASME 20th Joint Propulsion Conference, Cincinnati, OH, 11-15 June 1984.

46. Wortman, A., "Comments on "Improved Series Solutions of Falkner-Skan Equations,"" AIAA Journal, Vol. 24, No. 5, May 1986, p. 863.

47. Wortman, A., "Comments on "The Influence of Acceleration on Laminar Similar Boundary Layers,"" AIAA Journal, in Print.

48. Wortman, A., "Performance of Wind Turbines in Axial Vortex Flows," Submitted to the AIAA Journal.