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SHAKEDOWN AND PRELIMINARY TEST ON FIN TIP SIGNATURE MINIMIZATION AND APPENDAGE DRAG REDUCTION BY TIP JETS BLOWING

Prepared for:
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13. ABSTRACT (Maximum 200 words)

Preliminary experimental investigations of fin tip signature and appendage drag reduction using foil tip jets blowing were conducted. Water tunnel tests provided preliminary flow visualization data on how the jets affect the fin tip flow field and the near wake vortex roll-up process.

Through testing Model III, it was inferred that different jet blowing techniques might be required to attain vortex alleviation minimizing detectability and reducing appendage drag. For unswept fins, jet blowing from near the fin tip can alleviate the tip vortex flow effectively (within the observed range and test conditions of the experiment). It was observed that individual jet location, blowing momentum and direction are key control parameters of effectiveness in dispersion of vortices. It was found that lower-surface compared to upper-surface blowing was less effective. A combination of upper surface and fin tip jets at near trailing edge of the fin tip was shown to be effective for unswept fins. Near-total dispersion has been observed, implying that an optimum condition of blowing exists. Some new configurations of combined blowing from top, tip and bottom ports near the fin tip-trailing-edge may yield even better results and should be tried in the future.

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SHAKEDOWN AND PRELIMINARY TEST REPORT

I. INTRODUCTION

The preliminary experimental investigation of fin tip signature and appendage drag reduction using foil tip jets blowing were conducted by Engineering Research & Consulting, Inc. (ERCI). The experiments were carried out at The University of Tennessee Space Institute (UTSI) Water Tunnel under a subcontract arrangement. The water tunnel tests provided preliminary flow visualization data on how the jets affect the fin tip flow field and the near field wake vortex roll up process.

II. FACILITY DESCRIPTION

2.1 Water Tunnel

The UTSI Water Tunnel is a closed circuit, continuous flow facility especially designed for high quality flow visualization. Major components of the facility are illustrated in Figure 1. The circuit of the tunnel lies in a horizontal plane with the test section and a portion of the return circuit enclosed in a building. The test section is 12 inches high by 18 inches wide by 60 inches long and is constructed primarily of Plexiglas for versatility in observing and photographing the flow. Test section walls diverge slightly in the flow direction to maintain constant free stream velocity as the wall boundary layer thickens.

For this series of tests, a splitter (or "base") plate has been introduced to properly simulate the boundary layer at the base of the foil. This plate was designed parallel to the tunnel wall, with a rounded leading edge twelve inches in front of the hydrofoil.

The tunnel is powered by a one horsepower electric motor connected via a variable speed transmission to a 10 inch diameter, twin-bladed propeller in the return

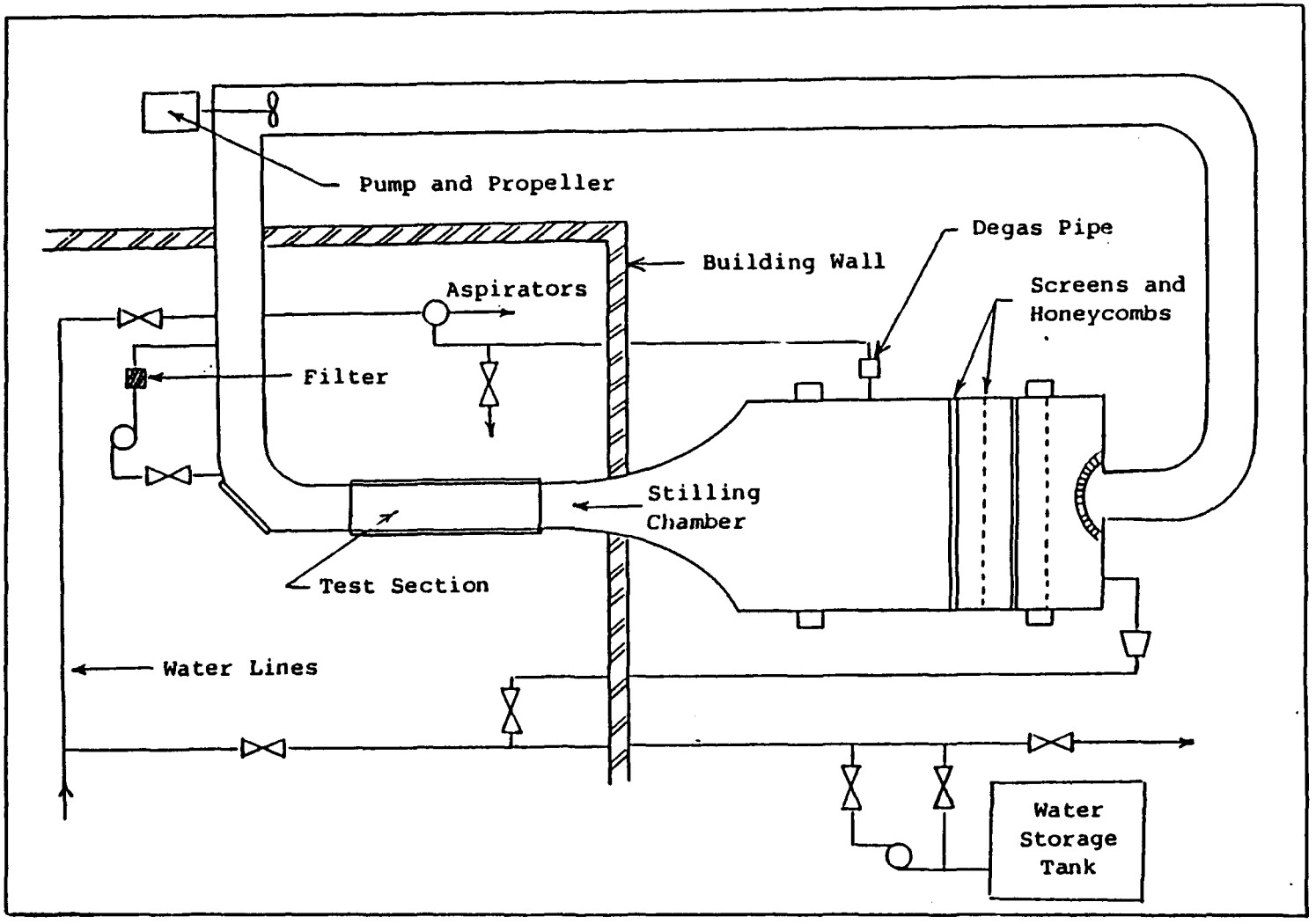


Figure 1. Schematic of Water Tunnel

leg of the circuit. This system permits continuous variation in test section velocity from 1 inch/sec to 20 inches/sec. For the present test, the free stream velocity was maintained at about 3.5 inches/sec.

The low turbulence and large windows in the UTSI Water Tunnel enable excellent photographs to be made of flow phenomena. The flow fields were recorded by color prints, color slides and videotapes. Luminescence was provided by two portable 500 watt, tungsten-halogen lamps.

2.2. Flow Visualization and Analysis

Data was acquired for each configuration by making vortices visible. Colored dyes were emitted from the surface of the foil model. This dye followed the roll up of vortices and made them visible for the entire length of the test section. The dye was a mixture of milk, alcohol and commercial food coloring. Care was taken to insure that a specific gravity of unity was achieved. The dye injection system consisted of pressurized dye reservoirs which supplied the dye to the model through 0.067 inch diameter tubes. Dye flow rate was adjusted by control of the pressure in a manifold connected to each dye reservoir. Dye flow rate was carefully controlled to insure that the dye velocity as it left the model did not produce its own jet effect. The low dye velocities also insured that the dye itself did not become unstable or transition to a turbulent stream. This insured that the streakline traced by the dye was turbulent or unsteady only if the flow itself was turbulent or unsteady.

Structure of flow fields were recorded using photographs and a video camera (Panasonic VSH Omni Movie PV-530). Using the recorded information, the effectiveness of each configuration was evaluated and assessed.

III. MODEL DESIGN AND INSTALLATION

The basic fin models used in the water tunnel tests were NACA 0012-64 foil sections with a semispan of 9.675 inches and a chord of 6.375 inches (see Appendix). Models were made of aluminum and painted white for improved photography. One end of the foil was mounted to a shaft extended through the base plate and side wall of the tunnel. The angle of attack α was controlled via the shaft and measured from an external reference. The foil tip jet ports, located at the opposite end of the foil, were at approximately 60 percent of the tunnel width. The foil was located forward in the test section to permit viewing as much of the roll up process as possible. The selected position--12 inches from the front of the test section--insured that the free stream was in good uniform condition and parallel to the model and yet permit visualization of vortex development for approximately 7 chord lengths downstream of the model trailing edge.

The models were designed such that interchangeable tips could be used to vary blowing configuration. In addition, during this preliminary test series, on-the-spot minor modifications to jet port configurations were also made. The tip configurations were chosen to assess the influence of changes in jet sweep angle, fin sweep angle, and different jet configurations. It would be a very lengthy process to test all the combinations of these parameters. Instead, judgment was made on each basic configuration and the test plan was modified accordingly in a research manner for understanding of flow physics and produce maximum results. A baseline design was chosen for the test and each subsequent configuration changed elements of the baseline design in order to determine the influences of those elements.

There were three sweep configurations of the fin models: unswept, backward swept and forward swept. All cases used a dihedral angle of zero, and a semispan of 9.675 inches. These configurations are described below.

TABLE 1. SWEPT MODEL DESCRIPTIONS

Configuration	Sweep Angle	Effective Chord Length
Unswept	0	6.375"
Backward Swept	30°	7.155"
Forward Swept	-30°	7.155"

Each fin base is attached with different tips for jet blowing. Two tips were designed originally. Type I tip utilizes tip jets which are mounted on the outboard edge of the fin as shown in Figure 2. Table 2 lists the jet configurations. Type II tips are slot jets located both on the upper and lower surfaces of the fin as shown in Figure 3. All jets can be individually controlled.

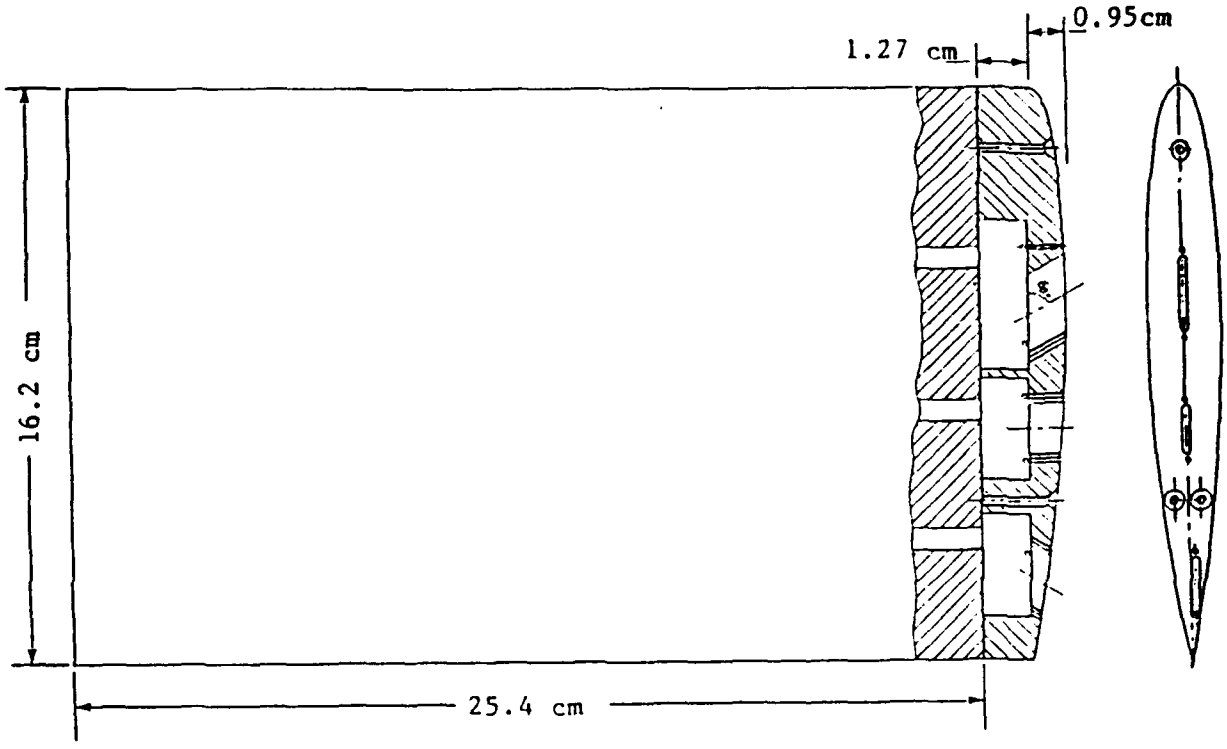
During the preliminary tests, modifications were made to the Type II jet slots to achieve optimum results. The final blowing slots used are smaller than the original design.

A new Type III tip was introduced which contained six circular holes located on both the upper and lower surfaces of the fin (Figure 4). Combinations of the jets were also utilized in the preliminary experiments. Selected jets were temporarily plugged to isolate effects of other jets.

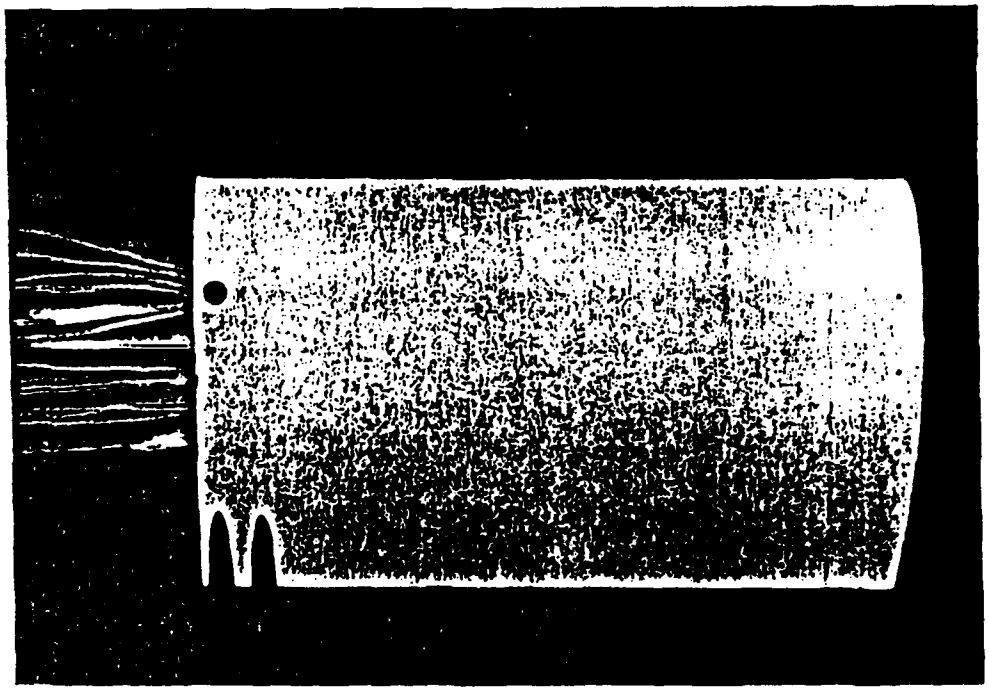
TABLE 2. TIP JET CONFIGURATIONS

Model	Configuration Design Parameter	Sweep Angles*	Dihedral Angles**
Rounded Tip	Dihedral	120° 90° 60°	0° 0° 15°

*Sweep angle measured along free stream direction in x-coordinate.
**Dihedral angle positive for upward blowing.



(a) drawing of the model



(b) photo of the model

Figure 2. Type I Tip Jets Configuration

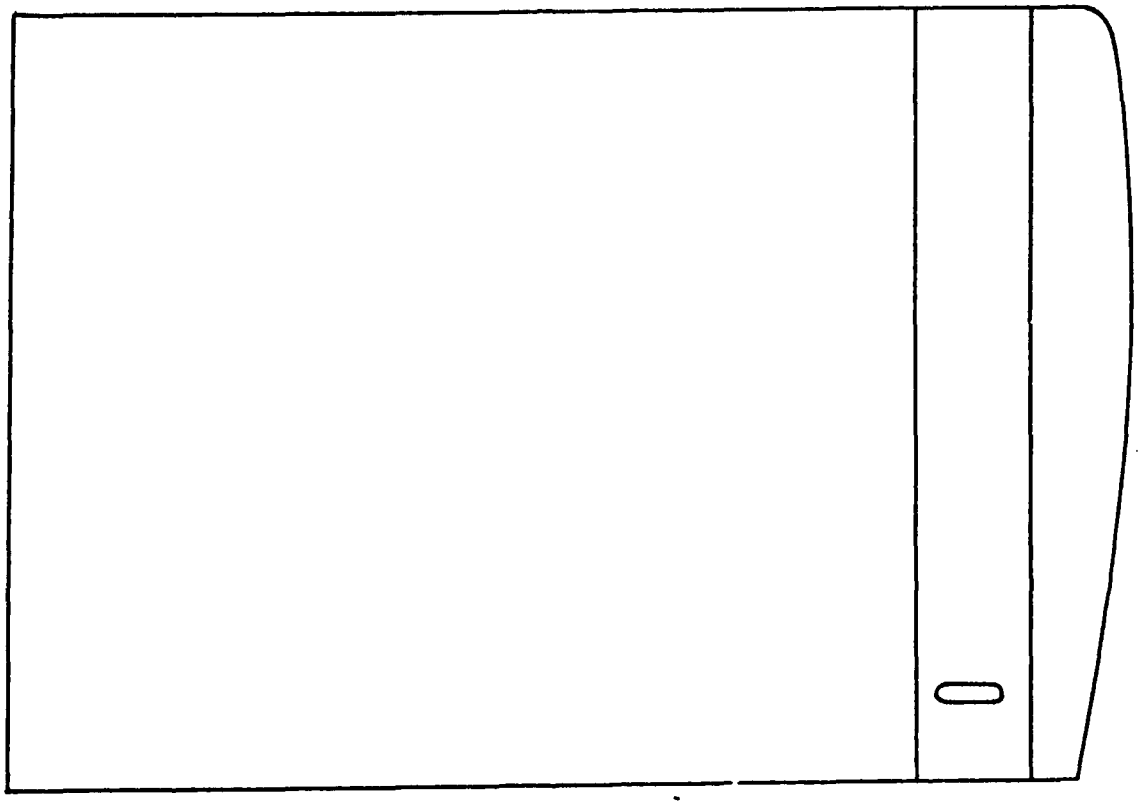


Figure 3. Type II Upper and Lower Surface Slot Jets

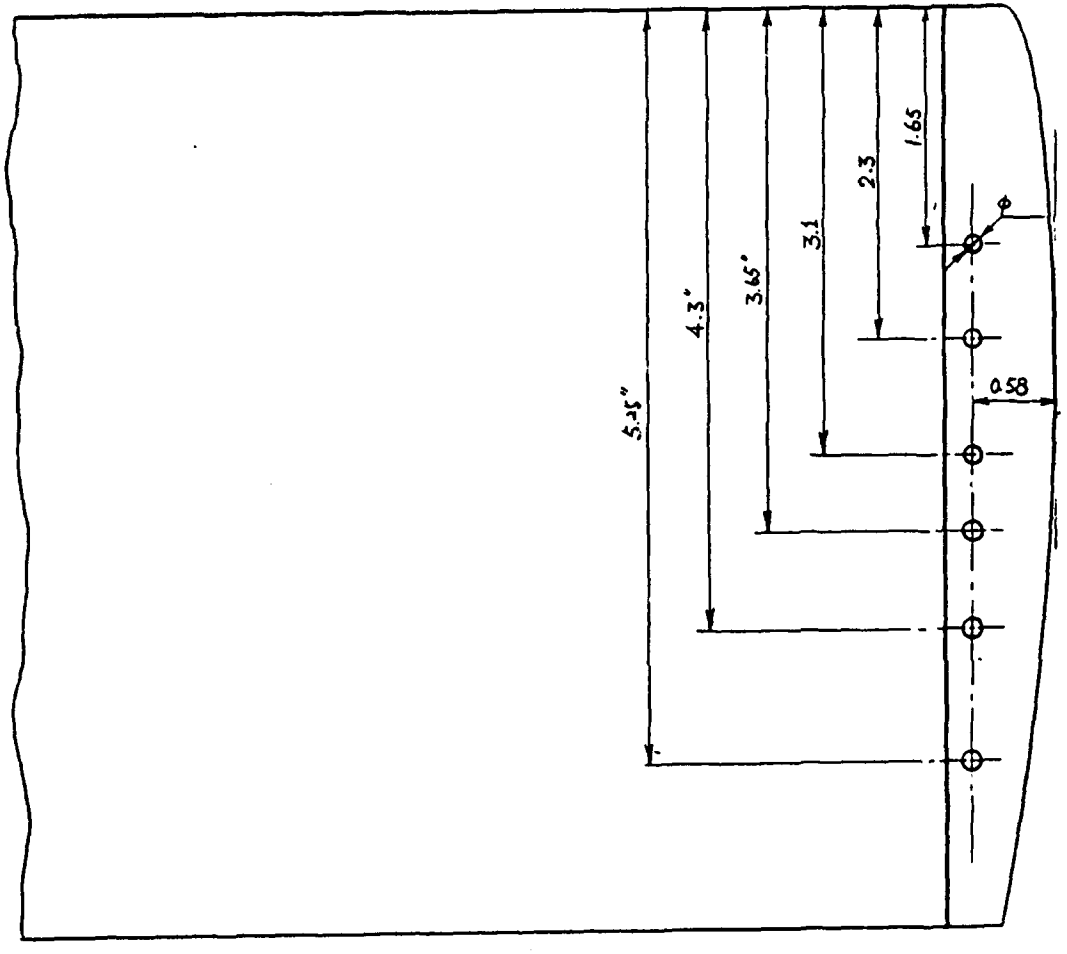


Figure 4. Type III Tip – Circular Jets (6 holes on both top and bottom surfaces)

IV. TEST CONDITIONS

Tests for each model involved variation of free stream flow rates, fin attack angles, jet blowing momentum coefficients and frequencies of jet pulsation. Free stream flow speed was maintained at 3.5 inches/sec for most of these preliminary tests but some higher speeds were also tested. Attack angles were ±4°, ±8°, and ±12°. The jet coefficient of a stream through a narrow opening is defined as

$$C_\mu = \frac{\rho_j A_j V_j^2}{q_\infty S_w} = \frac{\dot{m} V_j}{\frac{1}{2} \rho_\infty V_\infty^2 S_w}$$

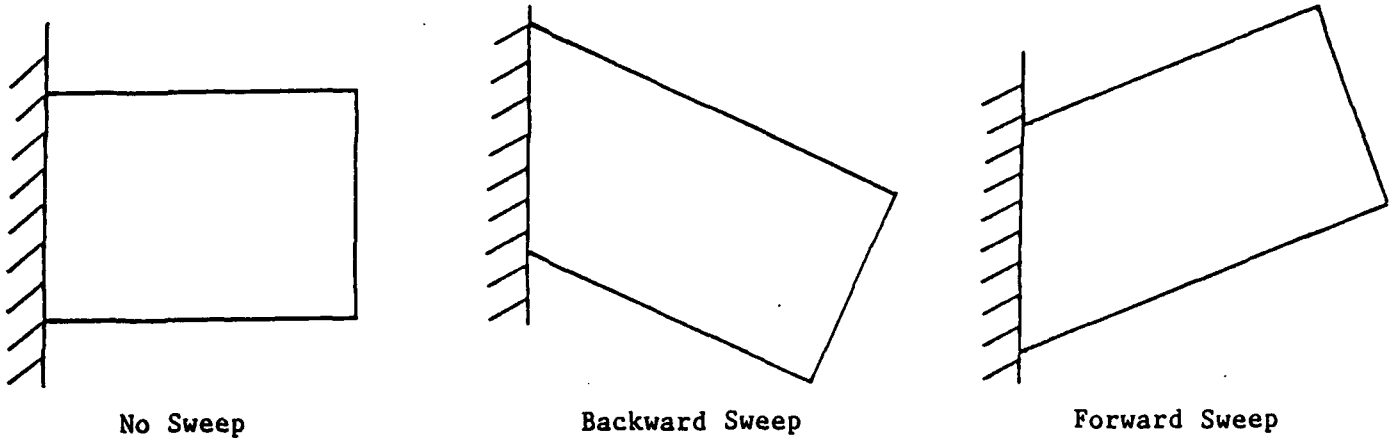
where C_μ is the jet momentum coefficient, V_j is the jet velocity, A_j is the jet port area, q_∞ is the free stream fluid dynamic pressure, S_W is the area of the fin and ρ_j is the density of the jet medium (water). Jet momentum coefficients were calculated based on the above formula. In order to adjust the C_μ, the velocity ratio of the jet to the free stream (V_j/V_∞) jet coefficients were varied.

Three models were used, unswept, backward swept and forward swept. Each model contained three types of tips as shown in Figures 2, 3 and 4. Selected jets were temporarily plugged to isolate effects of other jets during each experiment. The test model matrix is shown in Figure 5.

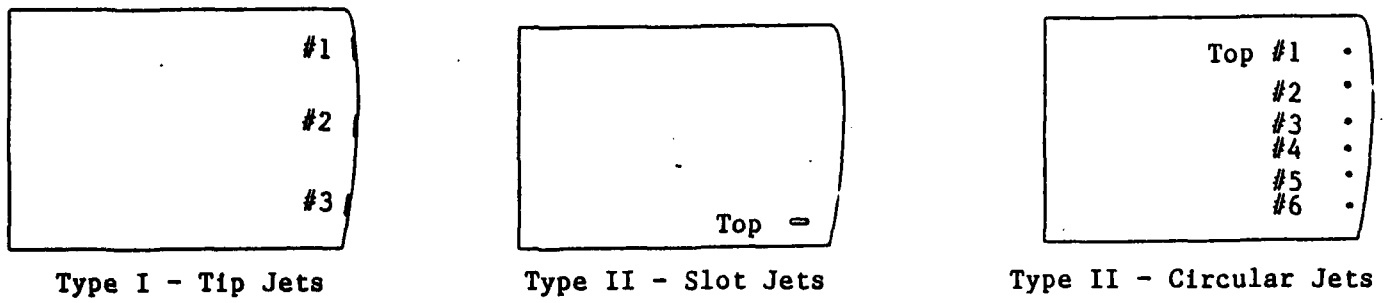
V. SHAKEDOWN AND PRELIMINARY TESTS

5.1 Shakedown Tests

The shakedown test constitutes the installation and use of portions of the final hardware. An unswept case with no root fillet was used. The shakedown test was used to verify the checkout procedures to install and adjust the base plate, attach dye and jet plumbing, assemble an unswept model, and adjust angles of attack and set up lighting, photography, etc.



(a) Sweep Configurations



(b) Jet Blowing Tip Configurations

Figure 5. Test Model Matrix

During this shakedown phase of tests, the Model III circular jets (Figure 4) were used. We have attempted to conduct not only the model and tunnel shakedown, but also to gain additional information on jet effects. Both the upper and lower jets were used in the shakedown tests which provided crucial information regarding upper and lower surface jet blowings.

The effort on this new jet configuration has paid-off handsomely. It has been proven that this model can be employed in identifying the effectiveness of location of the jet ports at the upper and lower surfaces of the fin.

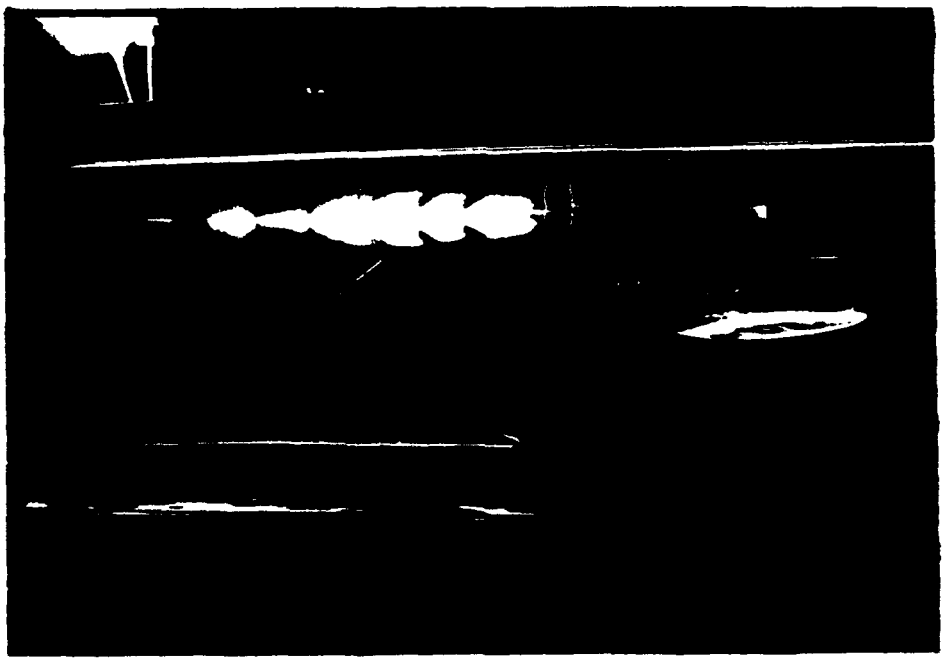
5.2 Preliminary Tests

Figure 5 shows the model matrix used in the experiments. Detailed drawings of the models are included in the appendix. The fin sweep angles used were: 0° (no sweep), 30° (backward sweep) and -30° (forward sweep). Three blowing tips were used: the tip jets (Type I), slot jets (Type II) and circular jets (Type III). In addition, selected combinations of the different types of jets were initiated in the preliminary optimization studies.

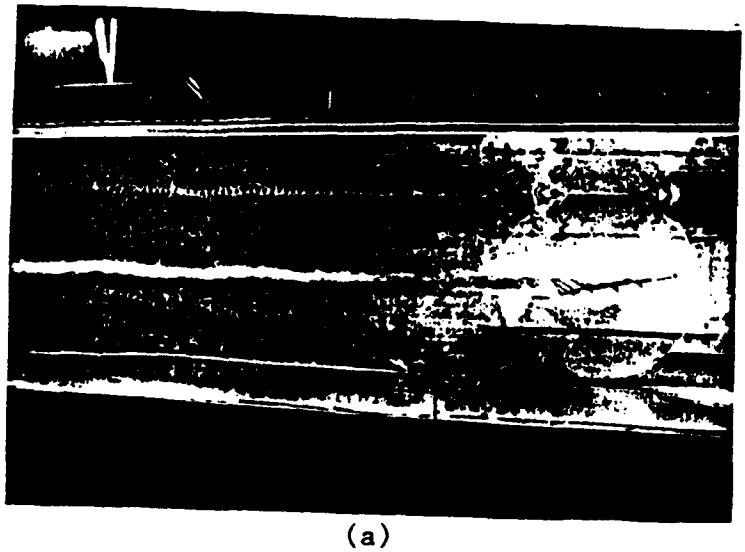
Results of the effectiveness of fin tip signature minimization and drag reduction by jet blowing were studied using the flow visualization technique. All key results were recorded on both still photos and by video. The video recording provides better observation of flow phenomena than the still photos.

Most of the experiments were conducted at flow speed 3.5 inches/sec and zero sweep. Sensitivity studies were made at higher speeds, backward and forward sweeps.

Figure 6 shows the fin tip signature and drag reduction (vortex dispersion) by tip jets (Type I) blowing at 12° angle of attack. Figure 6a shows the tight vortex roll up from the fin tip without blowing. The signature reduction resulting from tip jet blowing is very clearly shown in Figures 6b and 6c.



V_∞ = 3.5 in/s
α = 12°
no blowing

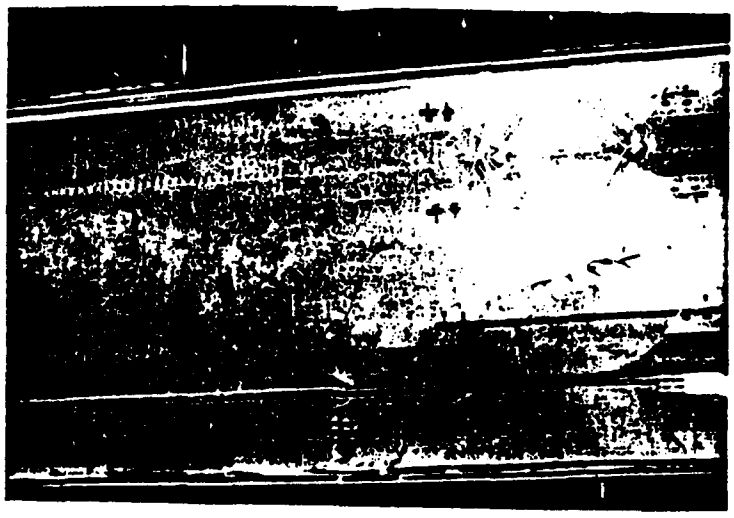


(a)

V_∞ = 3.5 in/s
α = 12°

Tip jets #2 and #3

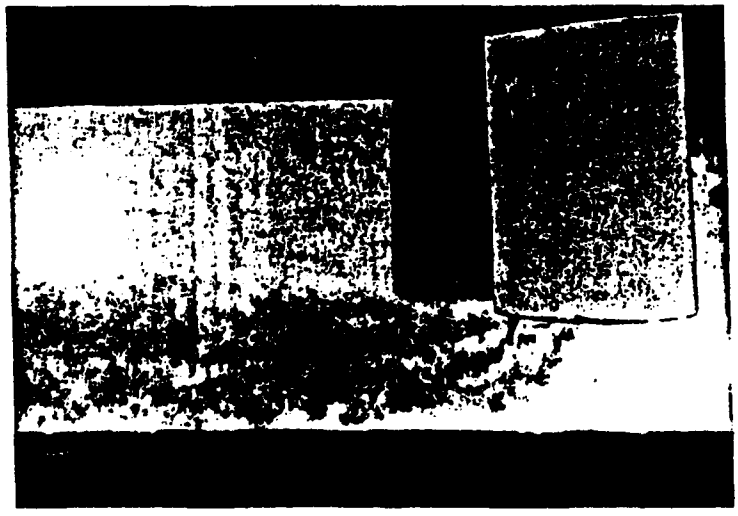
C_{μ_2} = 0.037
C_{μ_3} = 0.0076



(b)

Top View

Same condition as (b)



(c)

Figure 6. Fin Tip Signature Reduction by Tip Jets (Type I) Blowing

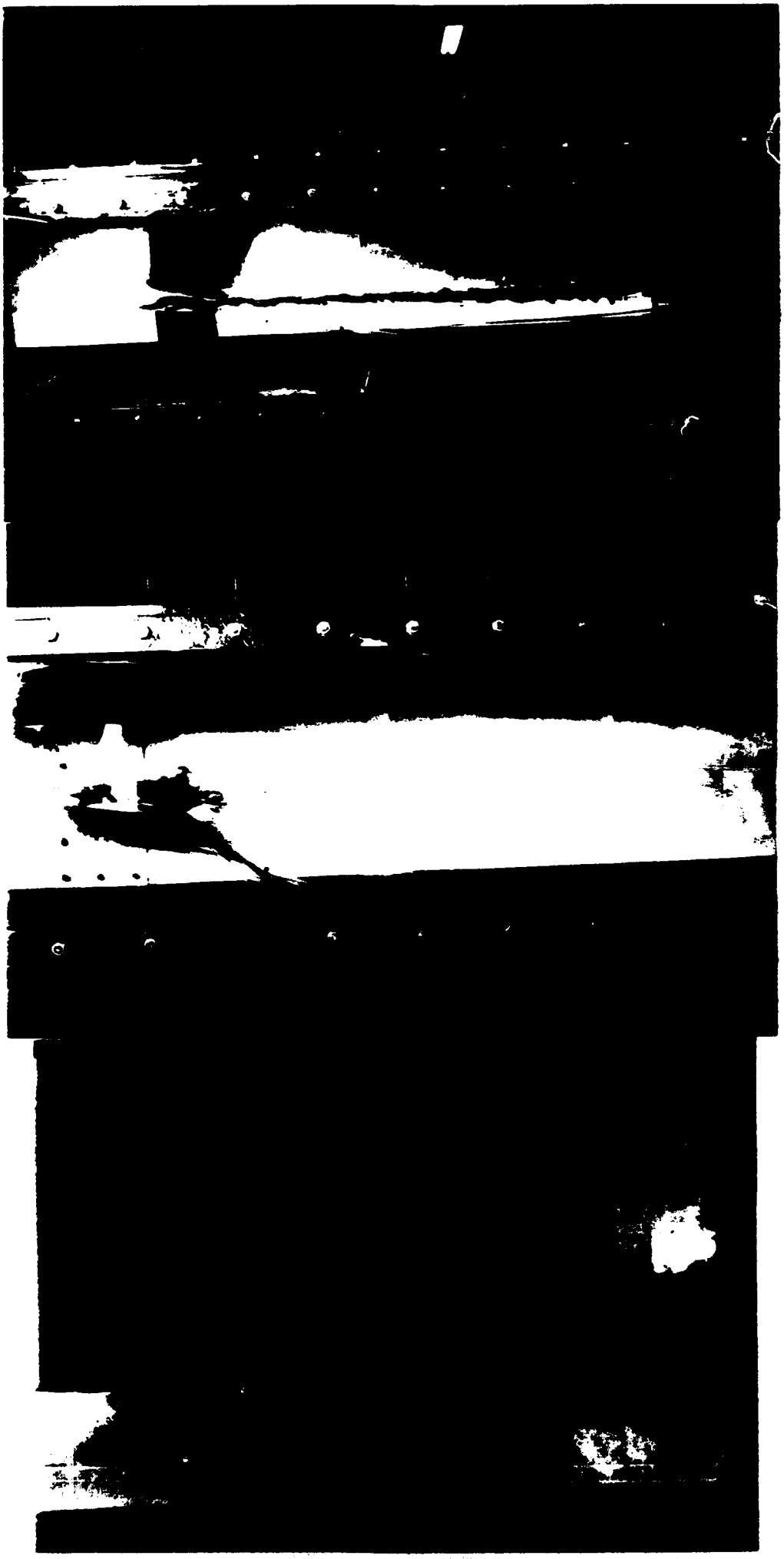
The effectiveness of the slot jet (Type II) blowing is shown in Figure 7. Figure 7a shows the fin at 8° angle of attack without blowing. At jet momentum coefficient $c\mu$ = 0.09, the vortex dispersion from the side view and top view are shown in Figures 7b and 7c. The vortex dispersion improves significantly with increased jet momentum from 0.09 to 0.36 as shown in Figure 8.

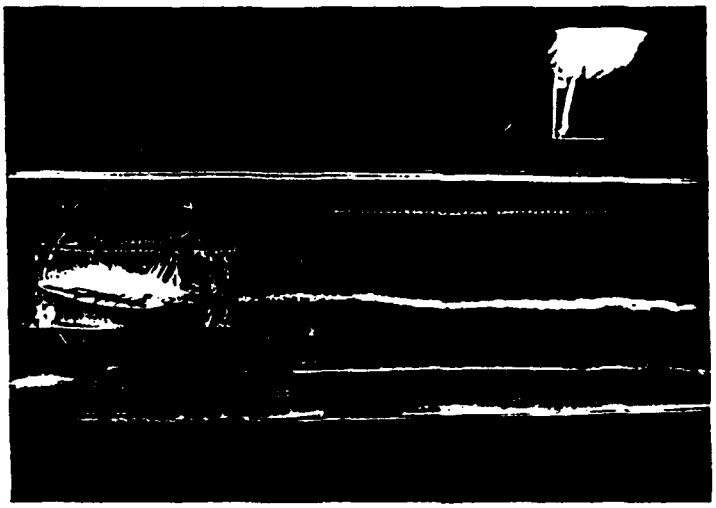
Figure 9 shows the circular jet (Type III) performance with upper and lower surface blowings. Figure 9a shows the no blowing vortex, while Figures 9b and 9c show the fin tip signature reduction by upper and lower surface jet blowing at the same jet momentum coefficient. It can be seen that the upper surface blowing is much more effective than the lower surface blowing. Consequently, the lower surface blowing technique is being eliminated.

A preliminary search for better combinations of port geometry was then initiated. It was discovered that the upper surface last circular port (circular jet #6) combined with the last tip jet (tip jet #3) gave an excellent vortex alleviation result for the unswept case. The tip vortex flow almost totally disappeared with about one-half of the jet momentum coefficient than any mentioned models as shown in Figure 10.

Figures 11, 12 and 13 show the flow field of the fin tip vortices with and without blowing of a backward swept fin. Figure 11a shows the model while Figures 11b and 11c show the fin tip vortices without blowing. The vortices are much more loosely rolled-up compared to the unswept fins as shown in Figures 6a, 7a, 8a and 9a. Three blowing configurations are shown in Figures 12 (top view) and 13 (side view).

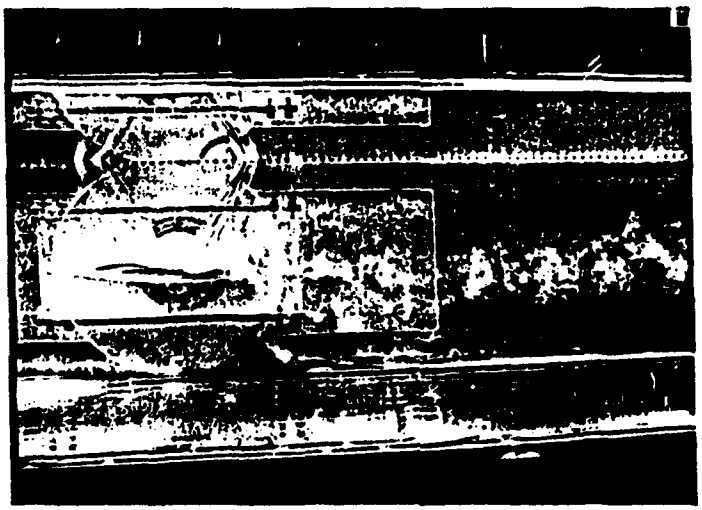
Identical experiments were carried out for the forward swept fin as shown in Figures 14, 15 and 16. Vortices are weaker for both the forward and backward swept fins. Consequently the jet blowing produces a lesser effect due to the originally weaker vortices. In the backswept cases, the trailing edges of the fins lie within the fin tip vortices. As a result, jet ports located near the trailing edge are less effective





V_∞ = 3.5 in/s
α = 8°
no blowing

(a)

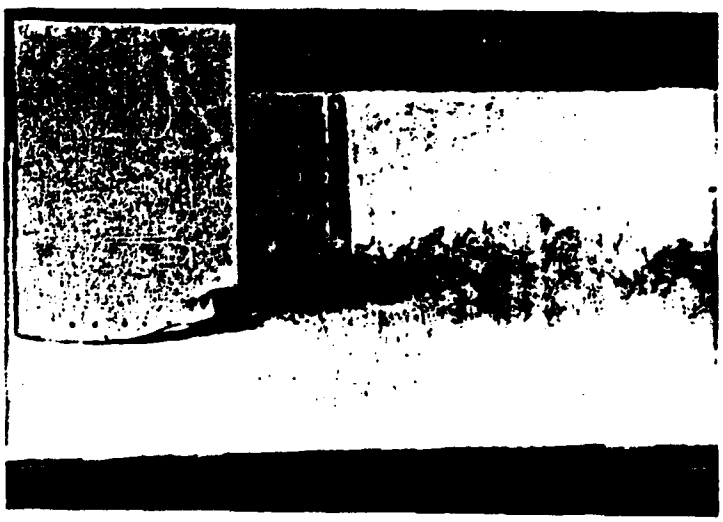


V_∞ = 3.5 in/s
α = 8°

Upper Slot Jet

C_μ = 0.09

(b)

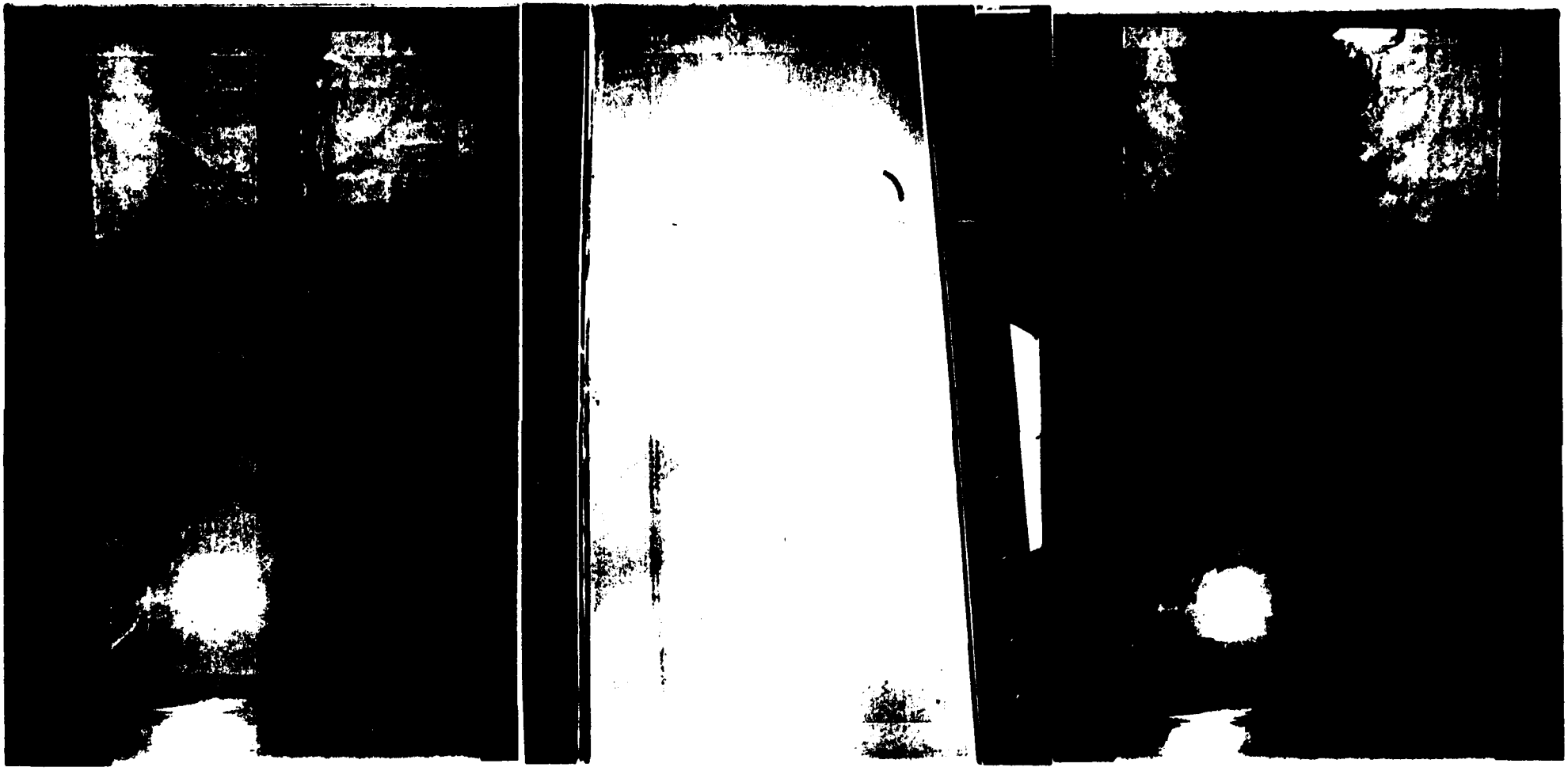


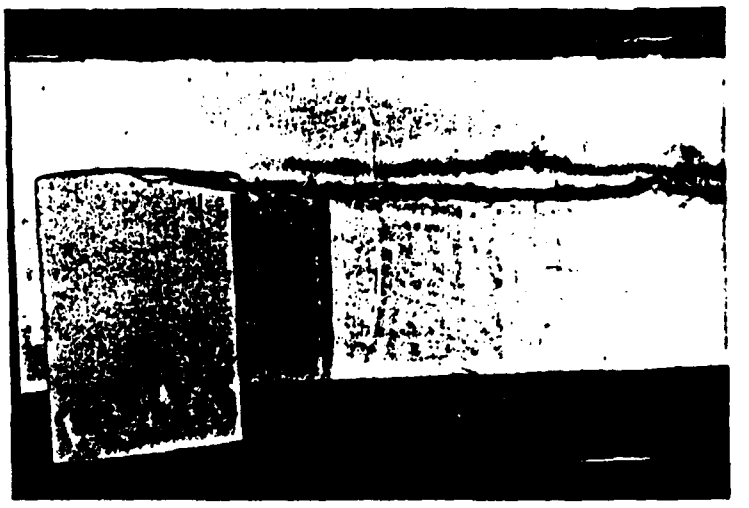
Top View

Same condition as above

(c)

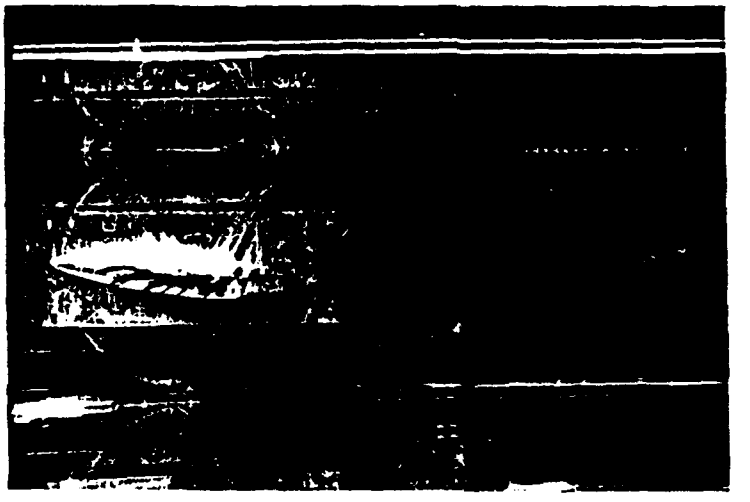
Figure 7. Fin Tip Signature Reduction by Slot Jet **(Type II) Blowing**





V_∞ = 3.5 in/s
α = 12°
no blowing

(a)

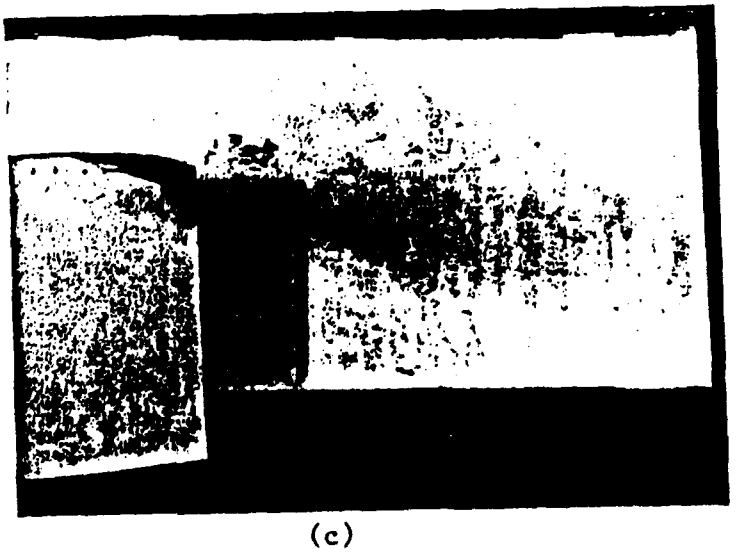


V_∞ = 3.5 in/s
α = 12°

Upper Slot Jet

C_μ = 0.36

(b)

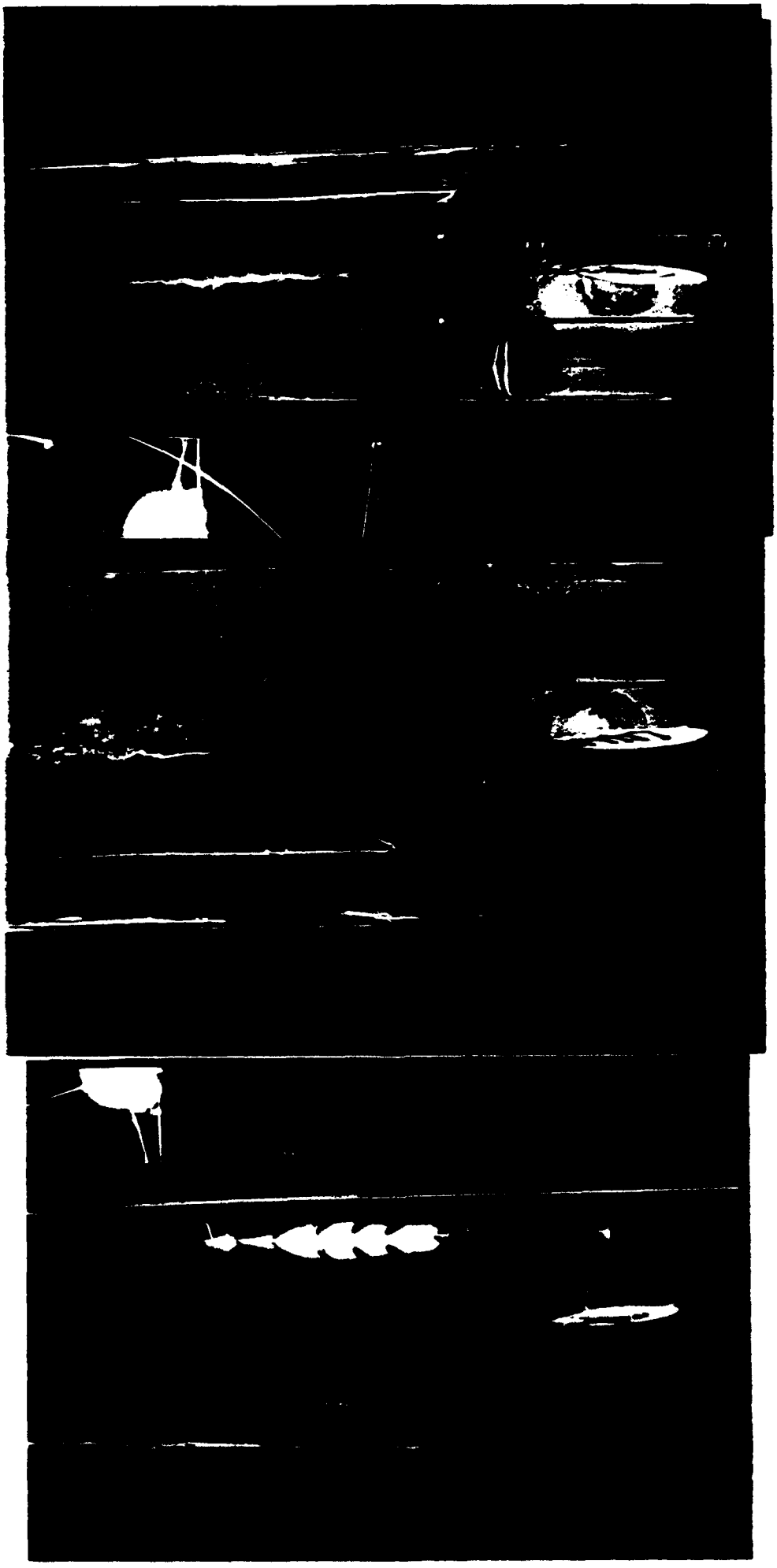


Top View

Same condition as above

(c)

Figure 8. Effects of Increased Jet Momentum Coefficient



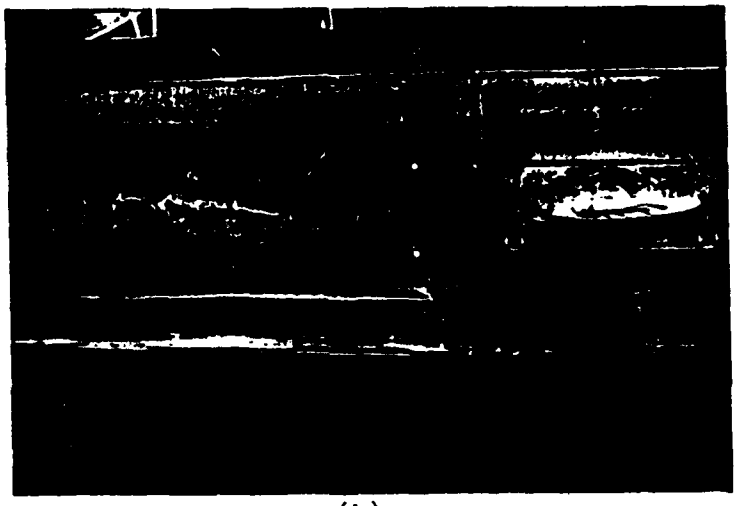
V_∞ = 3.5 in/s
α = -12°
no blowing

(a)

V_∞ = 3.5 in/s
α = 8°

Upper Circular Jets #4, 5, and 6

C_μ = 0.04

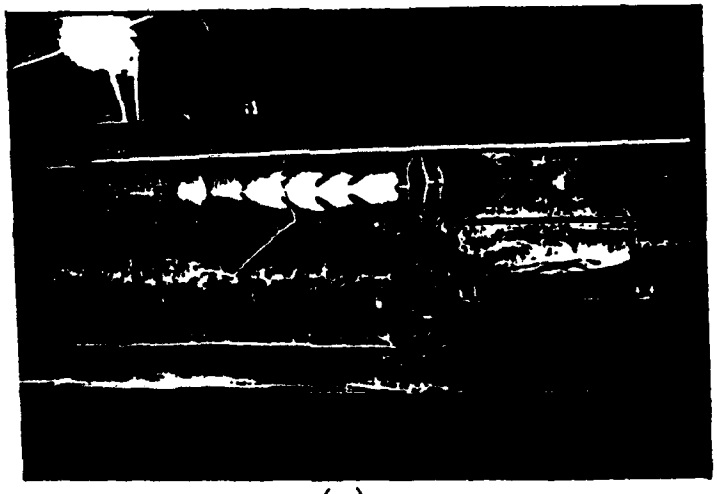


(b)

V_∞ = 3.5 in/s
α = 8°

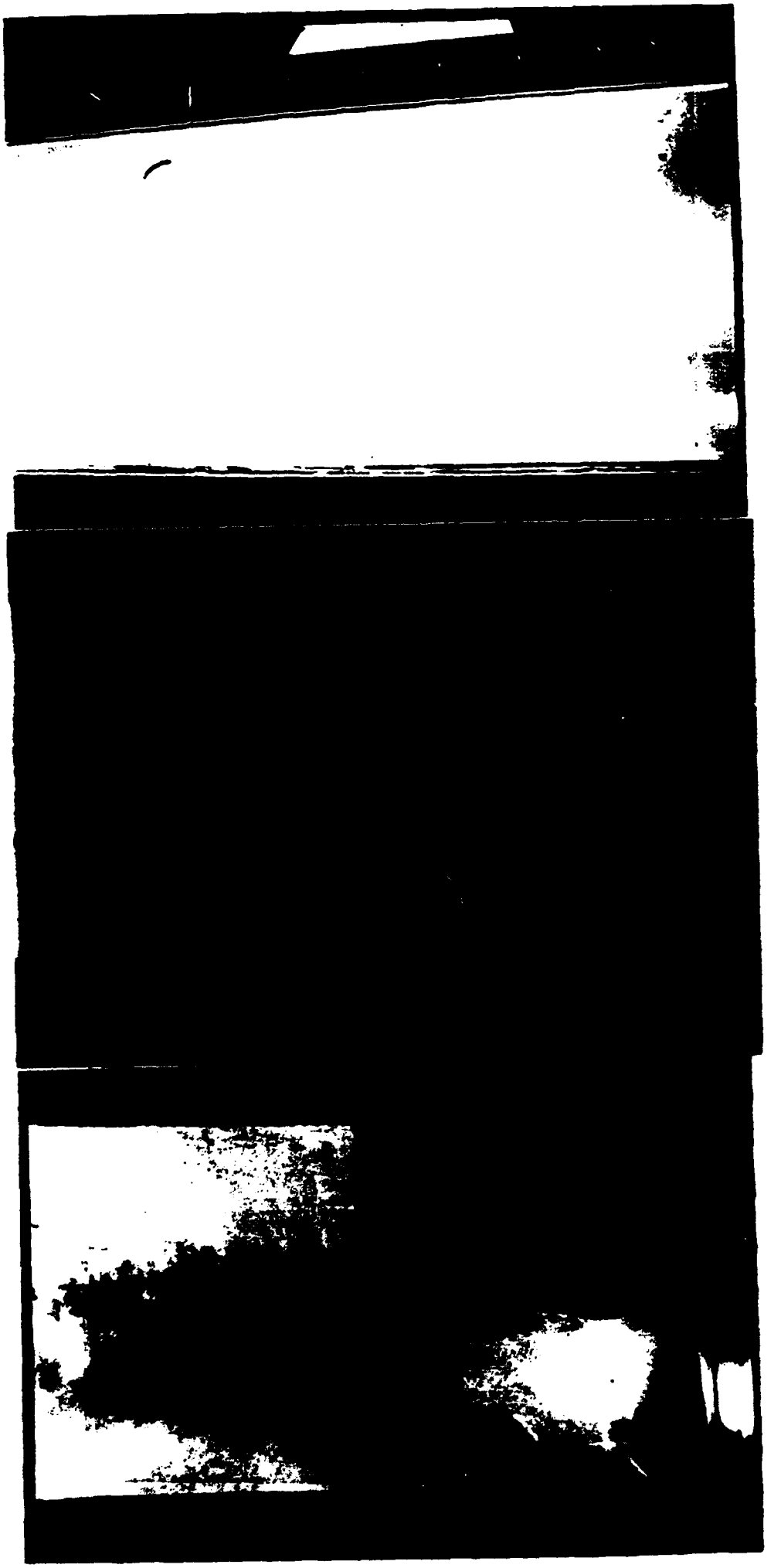
Lower Circular Jets #4, 5, and 6

C_μ = 0.04



(c)

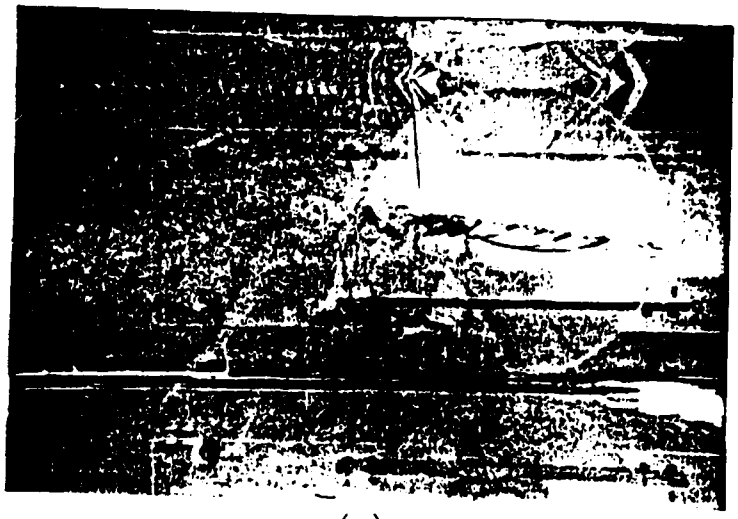
Figure 9. Fin Tip Signature Reduction by Upper and Lower Circular Jets (Type III) Blowing



V_∞ = 3.5 in/s
α = -8°

Lower Circular
Jet #6,
Tip Jet #3

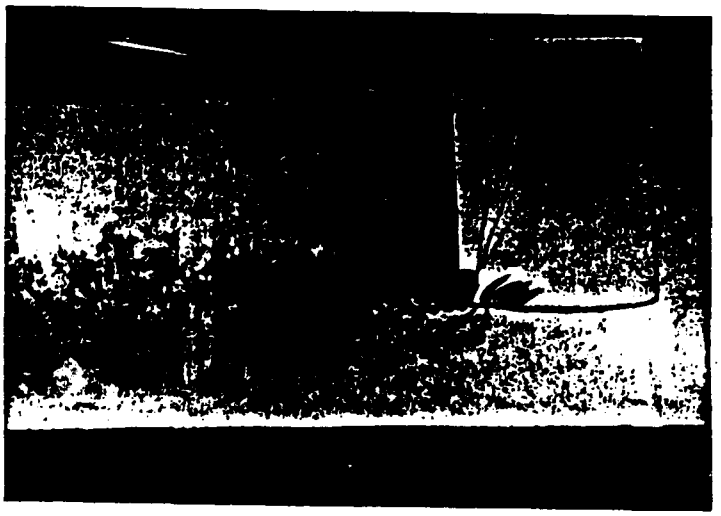
C_μ = 0.04



(a)

Top View

Same Condition
as above

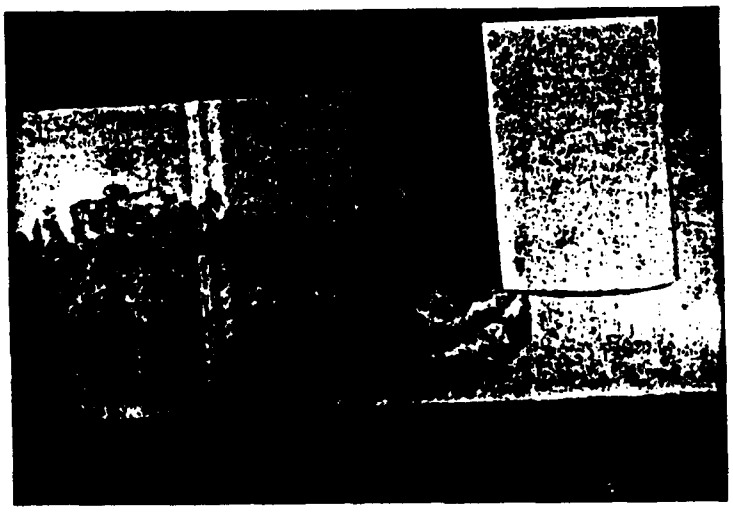


(b)

V_∞ = 3.5 in/s
α = -12°

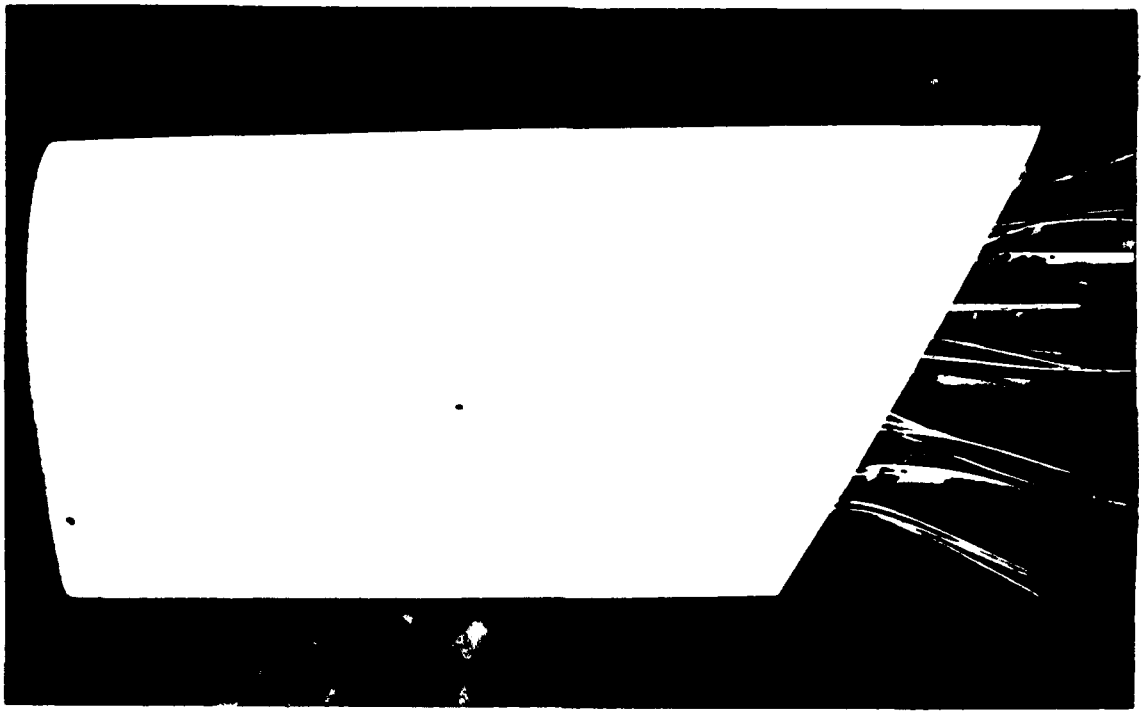
Lower Circular
Jet #6,
Tip Jet #3

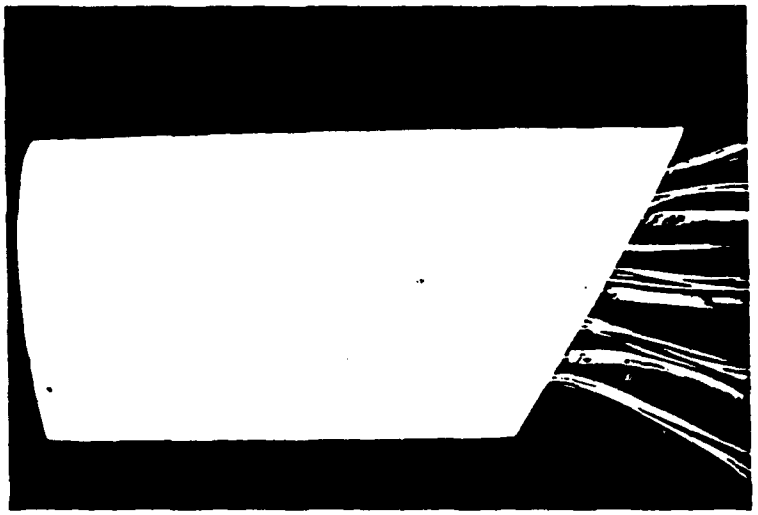
C_μ = 0.04



(c)

Figure 10. Combination of Circular and Tip Jets Blowing





30°
Backward Sweep
Model

(a)

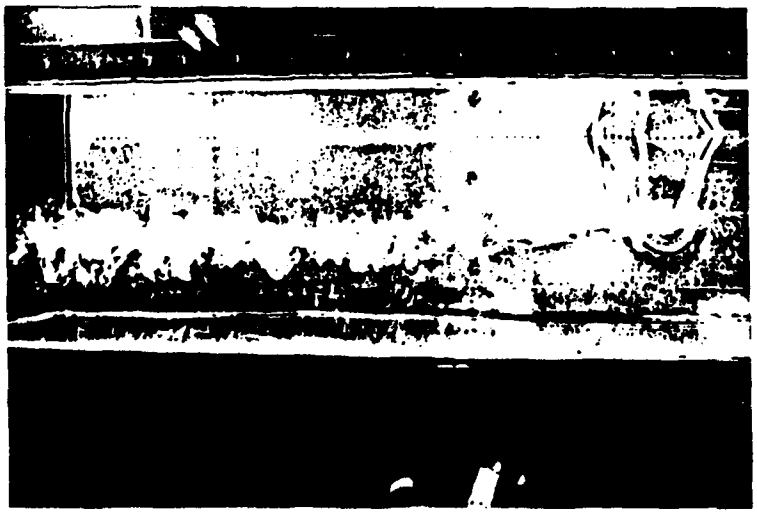
Backward Sweep 30°

V_∞ = 3.5 in/s

α = 8°

No Blowing

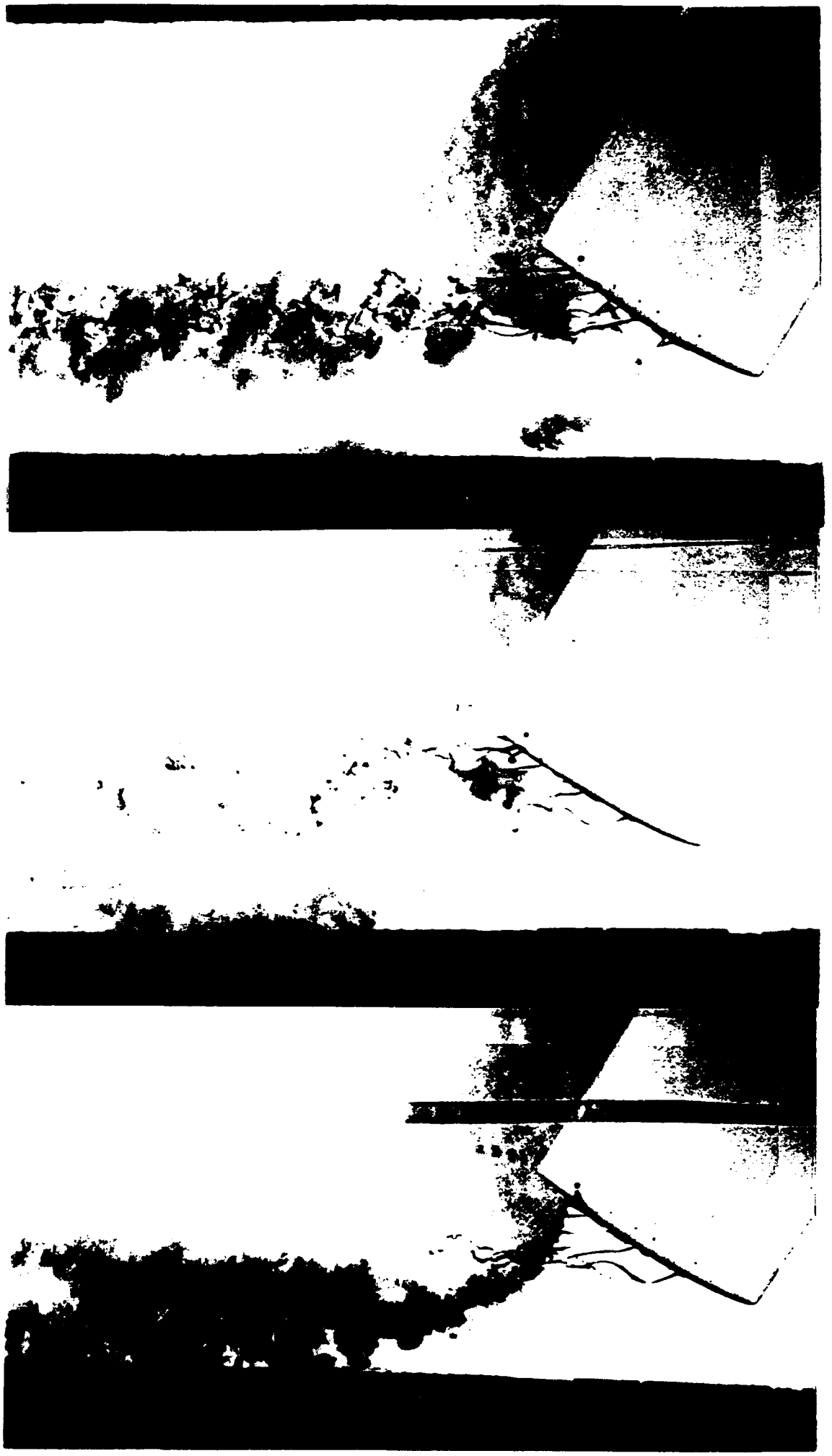
(b)



Side View of
(b)

(c)

Figure 11. Backward Sweep Model and Fin Tip Vortex



Backward Sweep 30°

V_∞ = 3.5 in/s

α = 8°

Tip Jet #1

C_μ = 0.016

(a)

Same Condition as (a) except

Tip Jet #2

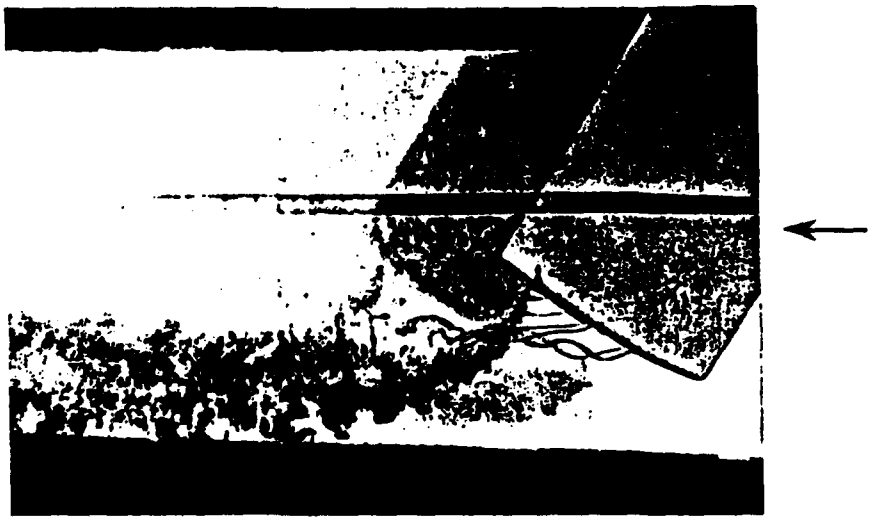
C_μ = 0.027

(b)

Same Condition as (a) except

Tip Jet #3 and Upper Circular Jet #6

C_μ = 0.017



(c)

Figure 12. Top View of Vortex Dispersion by Tip Jet Blowing of a Backward Sweep Fin

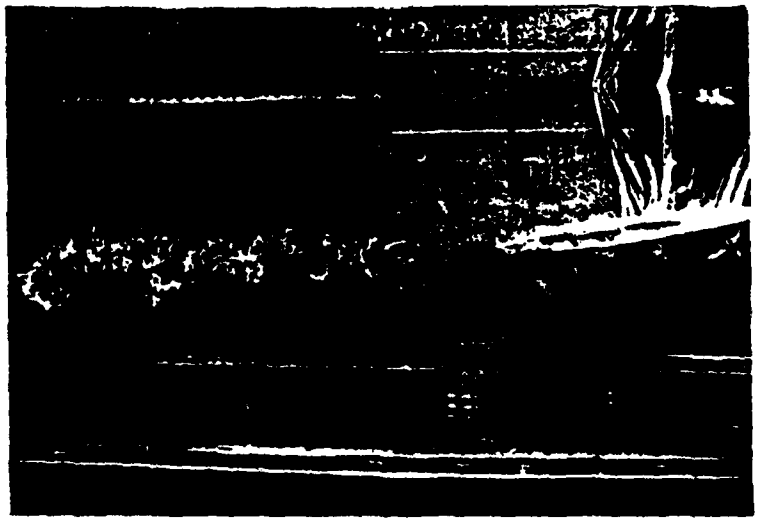
Backward
Sweep 30°

V_∞ = 3.5 in/s

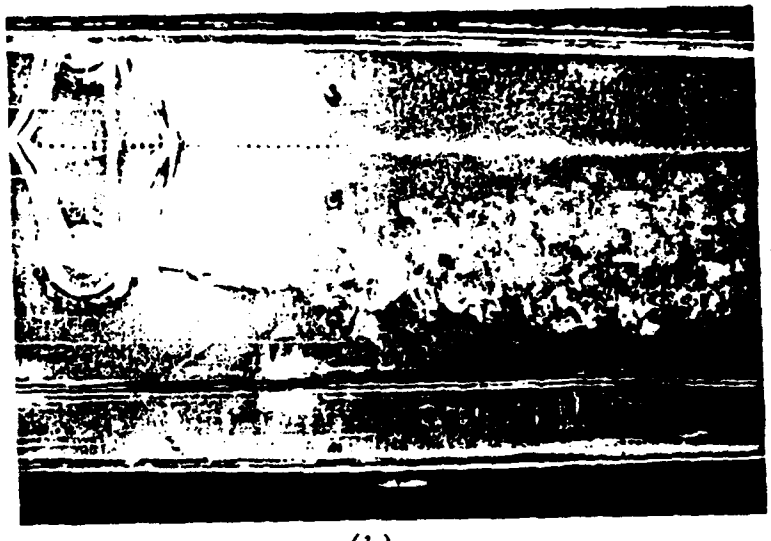
α = 8°

Tip Jet #1

C_μ = 0.016



(a)



Same Condition
as (a) except

Tip Jet #2

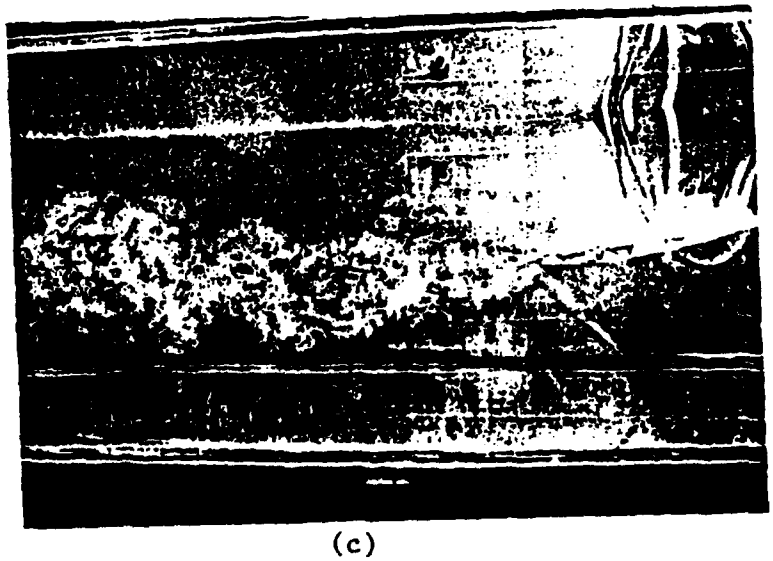
C_μ = 0.027

(b)

Same Condition
as (a) except

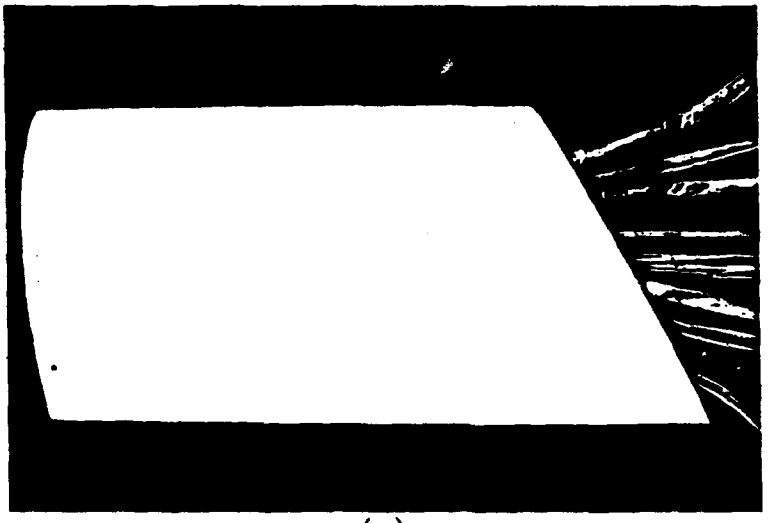
Tip Jet #3 and
Upper Surface
Circular
Jet #6

C_μ = 0.017



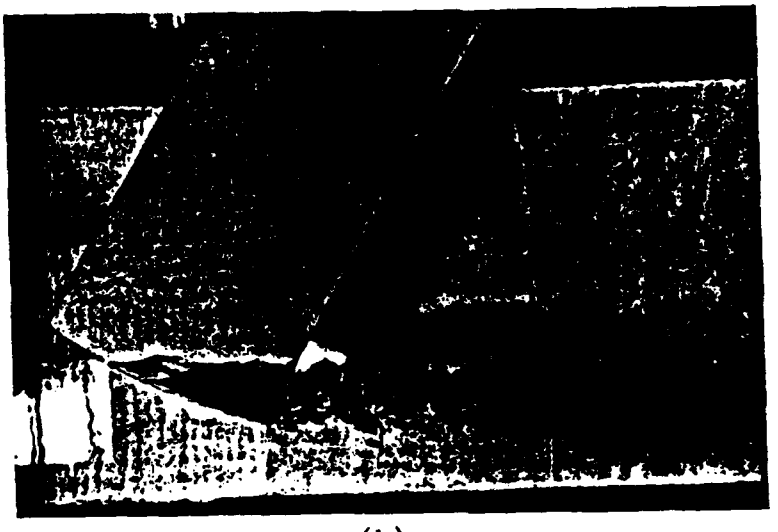
(c)

Figure 13. Side View of Vortex Dispersion by Tip Jet Blowing of a Backward Sweep Fin



30°
Forward Sweep
Model

(a)



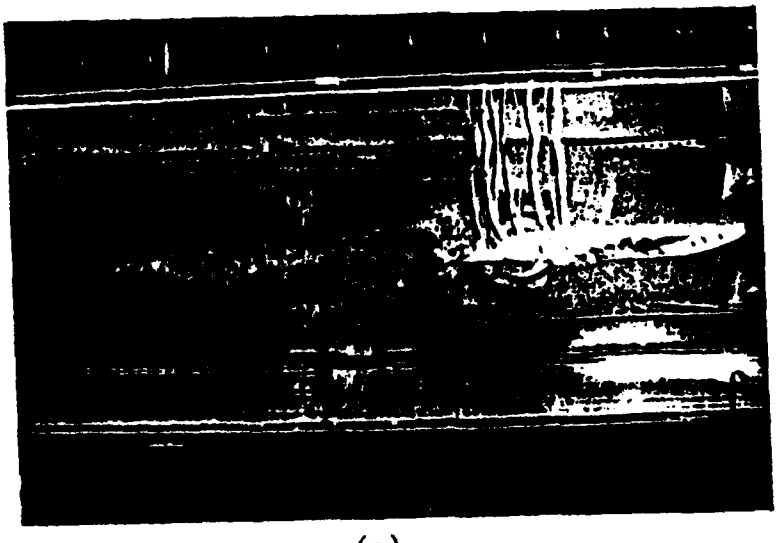
Forward Sweep 30°

V_∞ = 3.5 in/s

α = 8°

No Blowing

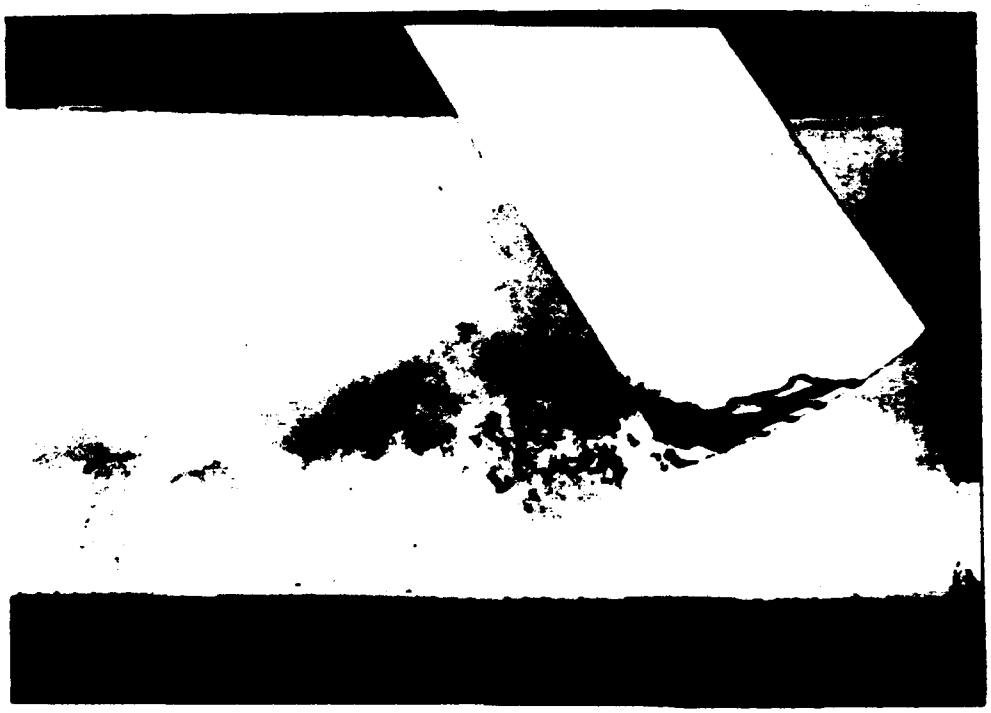
(b)



Side View of
(b)

(c)

Figure 14. Forward Sweep Model and Fin Tip Vortex



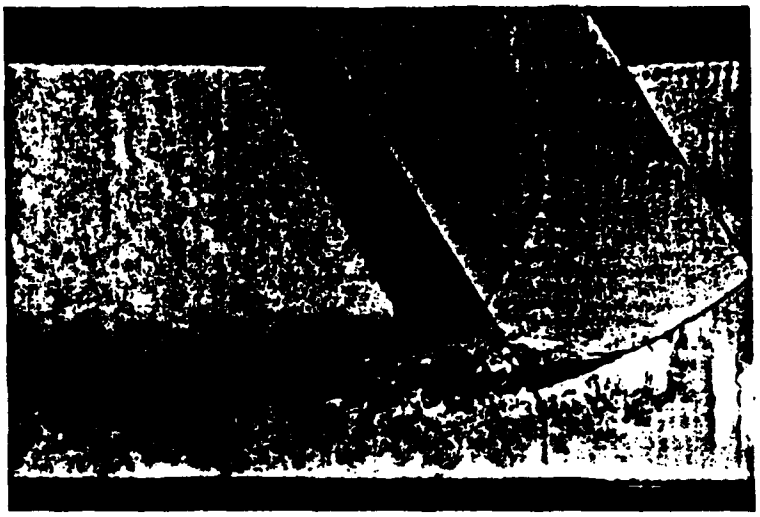
Forward Sweep 30°

V_∞ = 3.5 in/s

α = 8°

Tip Jet #1

C_μ = 0.037



(a)

Same Condition as (a) except

Tip Jet #2

C_μ = 0.06

(b)

Same Condition as (a) except

Tip Jet #3 and Upper Circular Jet #6

C_μ = 0.039

(c)

Figure 15. Top View of Vortex Dispersion by Tip Jet Blowing of a Forward Sweep Fin

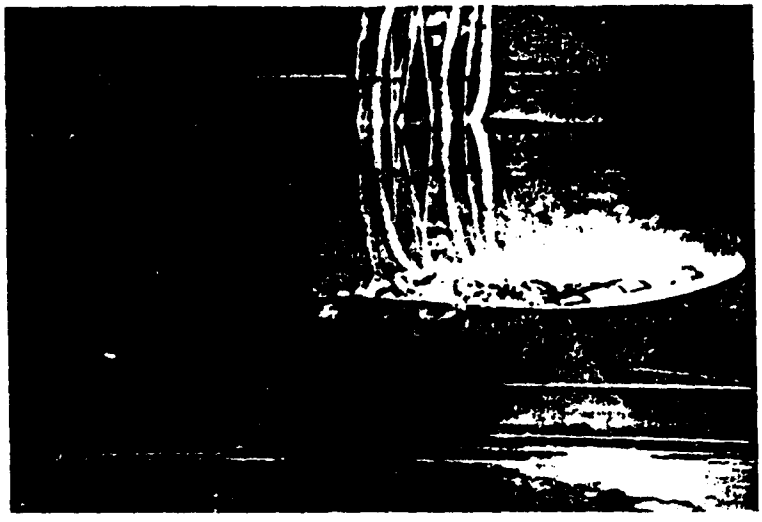
Forward Sweep 30°

V_∞ = 3.5 in/s

α = 8°

Tip Jet #1

C_μ = 0.037

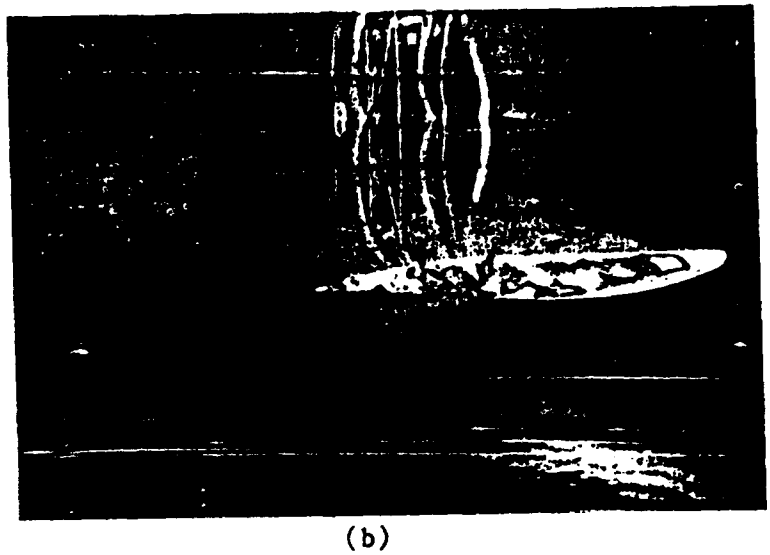


(a)

Same Condition as (a) except

Tip Jet #2

C_μ = 0.06

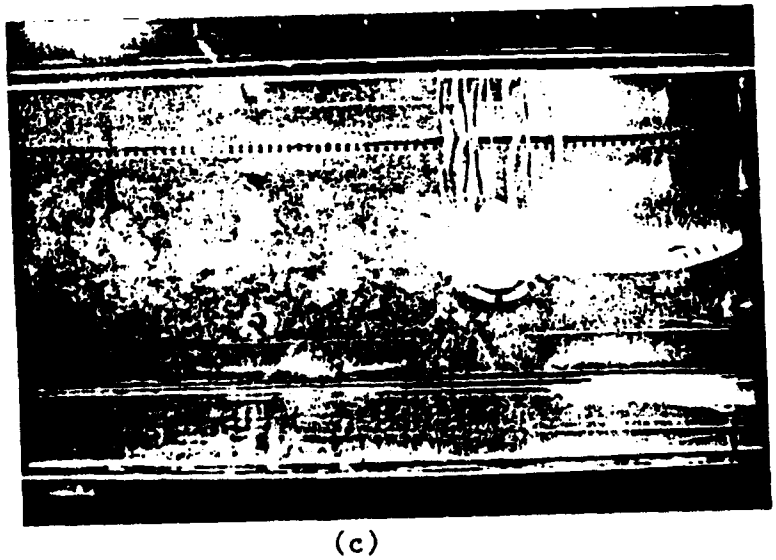


(b)

Same Condition as (a) except

Tip Jet #3 and Upper Circular Jet #6

C_μ = 0.039



(c)

Figure 16. Side View of Vortex Dispersion by Tip Jet Blowing of a Forward Sweep Fin

compared to the jets located near the mid-chord. This is contrary to the unswept and forward swept cases.

Base plate suction has insignificant effects on the fin tip vortex dispersion. This is due to the large distance separating the two effects. In general, up surface suction strengthens the vortices while blowing weakens the vortices. At higher speed the fin tip vortices are stronger. As a result, the jet blowing plays a more significant role in dispersing the vortices.

VI. PRELIMINARY CONCLUSIONS

1. There are two goals for discrete jet blowing: (1) vortex alleviation to minimize the detectability and (2) to reduce appendage drag. By the testing of Model III, it has been proven that different jet blowing techniques might be required to attain these separate goals.
2. It has been proven that for the unswept fins the jet blowings from near the fin tip can alleviate the tip vortex flow effectively (at least within the observed range of about seven chord lengths downstream and the test condition of this experiment).
3. It was observed that the individual jet location, blowing momentum and direction are the key control parameters of effectiveness in dispersion of vortices.
4. It was found that lower surface blowing (at positive angle of attack) was less effective.
5. A combination of upper surface and fin tip jets at near trailing edge of the fin tip has been proven to be most effective for the unswept fins. A result of almost total dispersion has been observed. This implies that an optimum condition of blowing exists and can be found with careful experiments.
6. Some new configurations of blowing from top, tip and bottom ports near the fin tip-trailing-edge may yield even better results and will be tried in the future.

VII. RECOMMENDATIONS

Owing to the successful results obtained during the preliminary tests, quantitative experiments and more detailed measurements should be made. Furthermore, assessments of the jet performance and wake behavior should be included in the Phase II experiments. The following program is recommended to refine the experiments which ultimately will lead to new design and modifications to the fins to significantly reduce the fin tip signature and appendage drag.

A. Further Water Tunnel Tests

1. Selection of optimum jet ports location, shapes and test in various conditions. (Original Phase II program)
2. Detail jet/vortex interactions with improved flow visualization techniques.
3. Near-field (3-4 chord lengths) downstream vorticity distribution measurements.

B. Wind Tunnel Tests

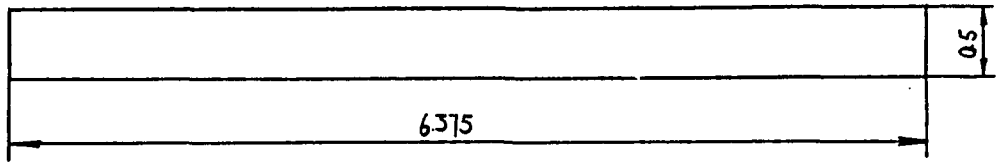
1. Lift measurements on selected jet blowings.
2. Drag measurements on selected jet blowings.

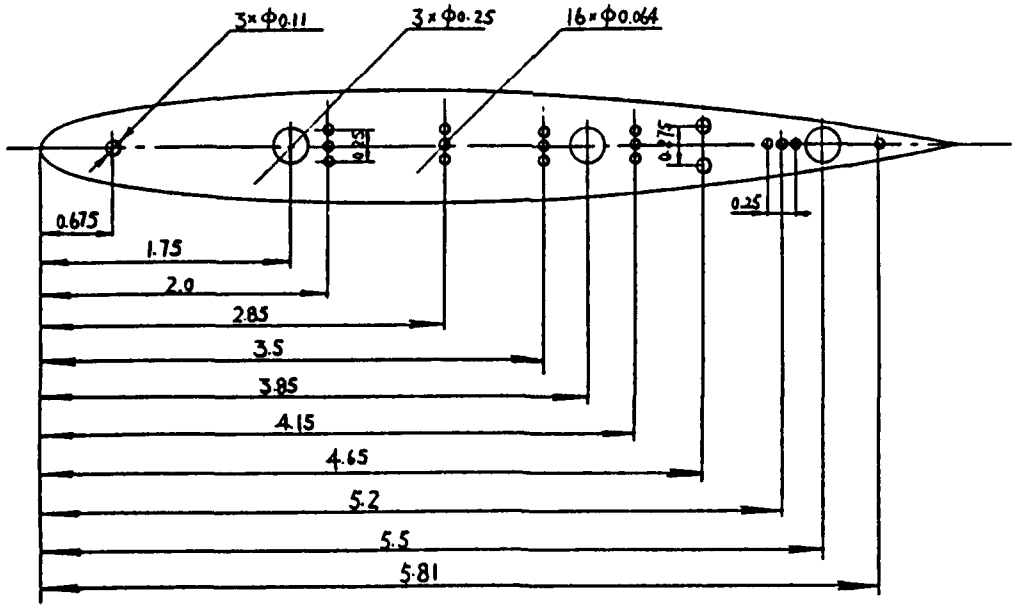
C. Assessments on the Wake and Performance of Jet Blowing

1. Mid-field/(far-field) wake behavior assessments.
2. Performance assessment based on data from water and wind tunnel measurements.

APPENDIX

Blueprints of Models



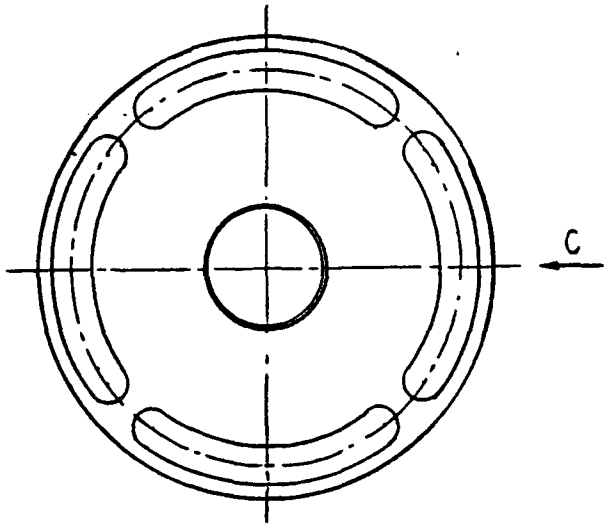


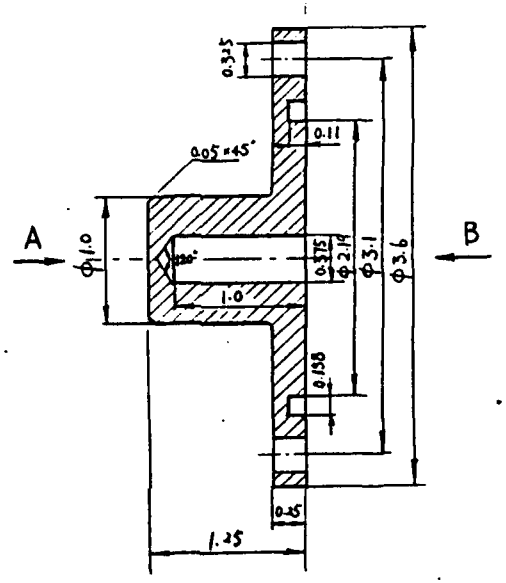
Notes:

1. Airfoil Type
   NACA 0012-64

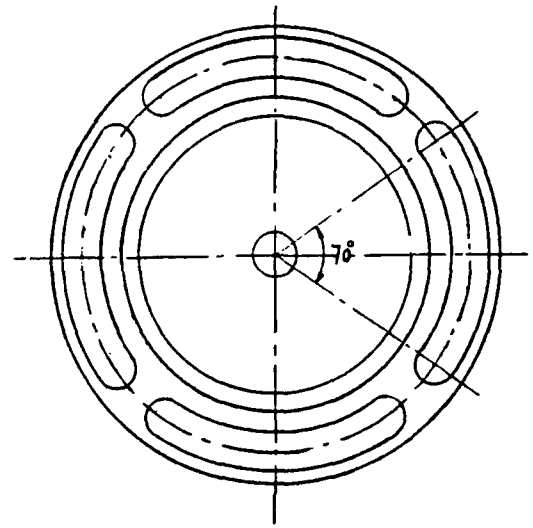
2. Material:
   Aluminum

A - View

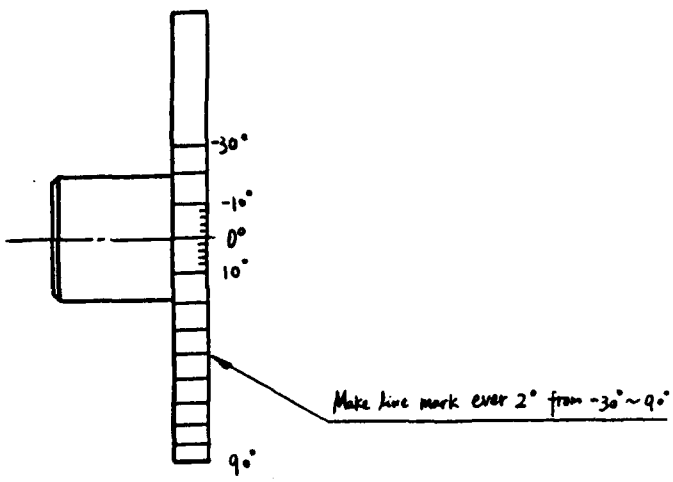




B - View

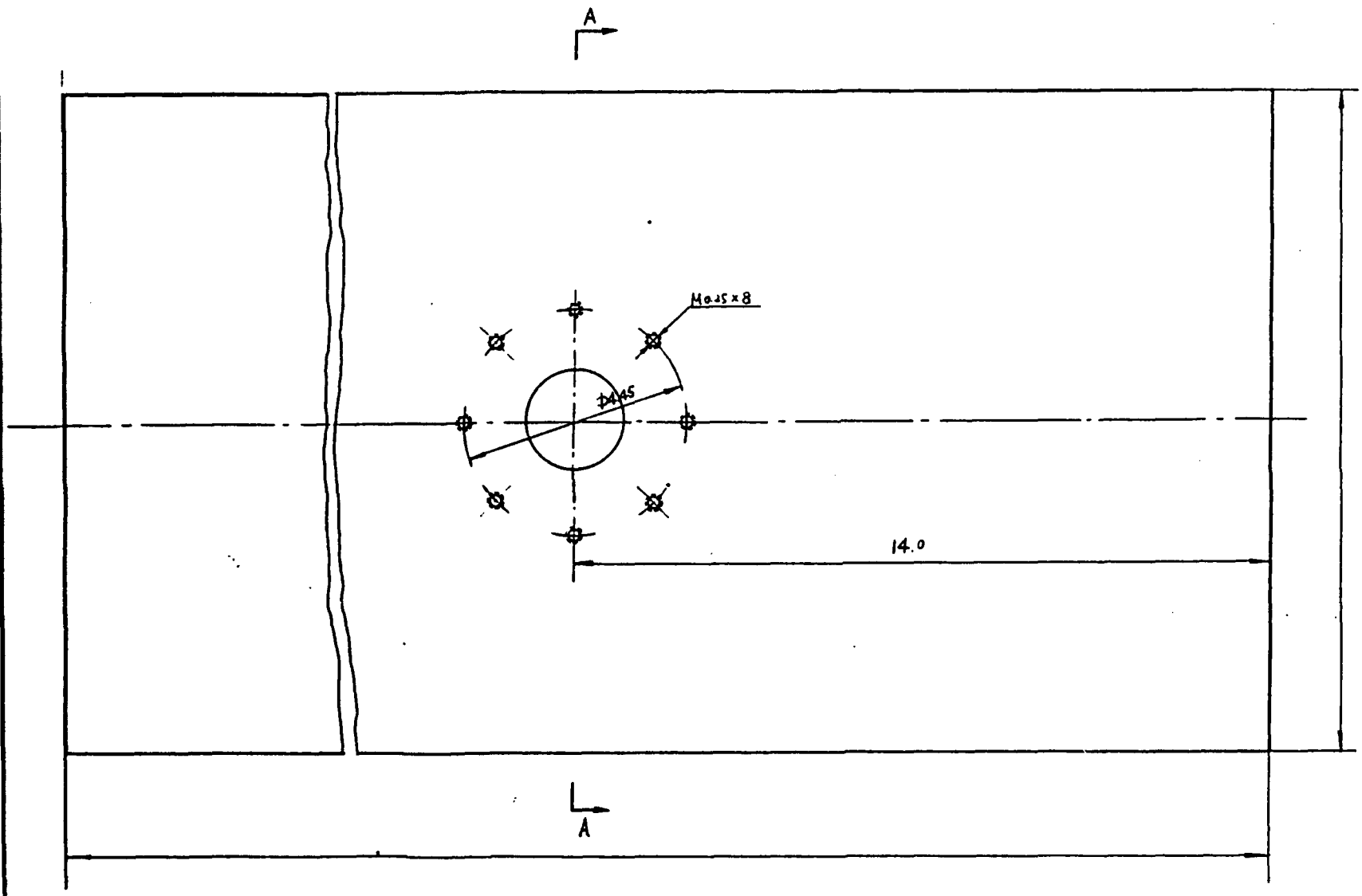


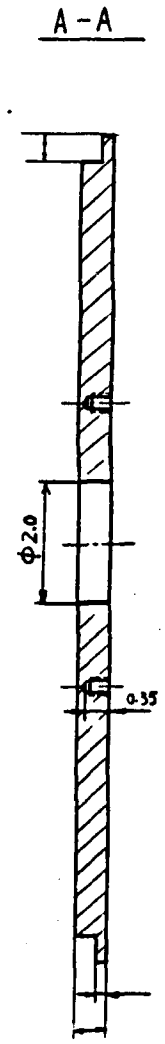
C - View



Material: Aluminum

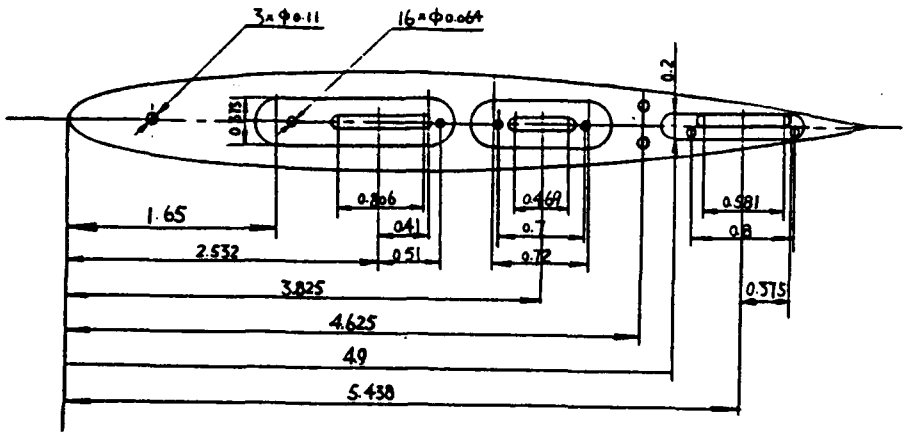
Water Tunnel Adapter Plate for Sidewall



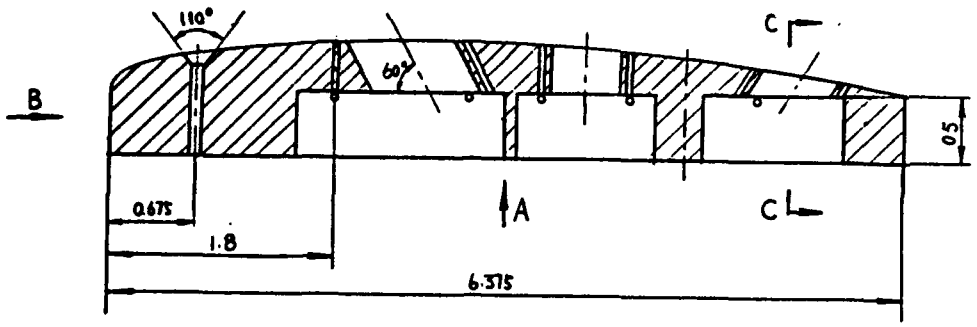


Water Tunnel Sidewall

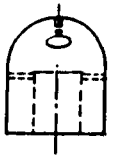
A-View



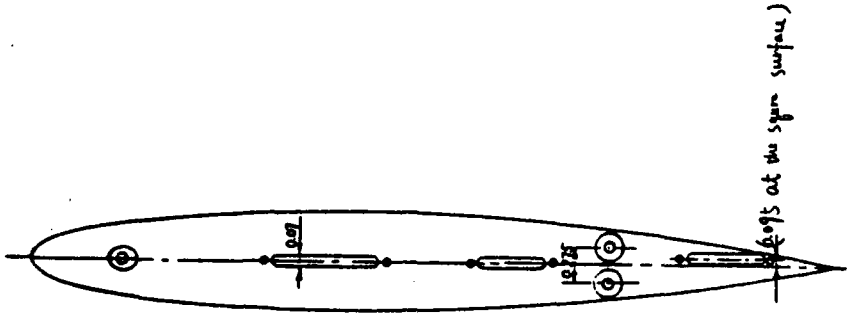
Round Tip



B-VIEW



C-C SECTIOT



Notes:

1. Airfoil Type:
   NACA 0012-64

2. All Slots Edge Rounded:
   R = 0.01 ~ 0.05

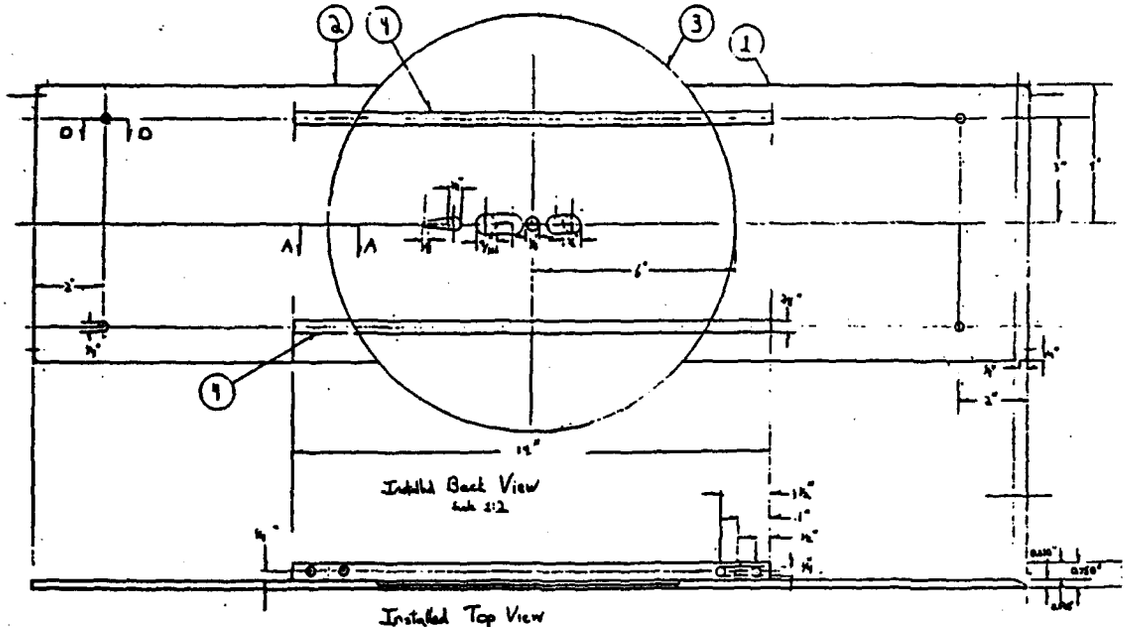
3. Material: Aluminum

Plate Assembly

Eric Engelmann

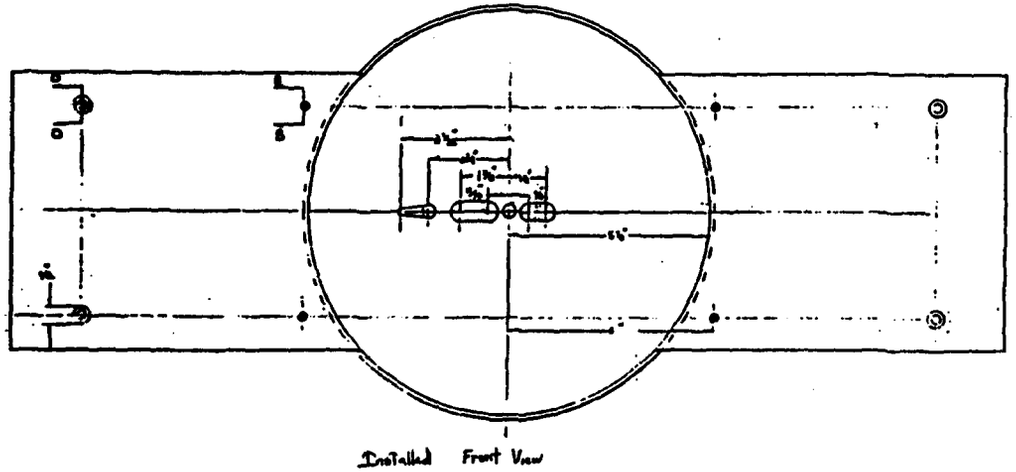
ERCI

DATE 6/5/89 | APPROVED BY ADV 6/7/89

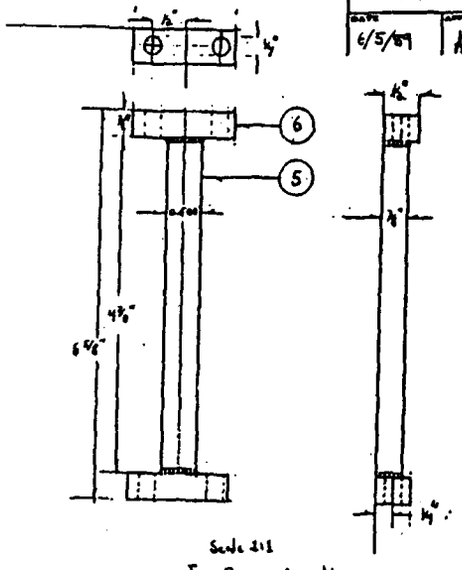


Installed Back View
Scale 1:2

Installed Top View
Scale 1:2

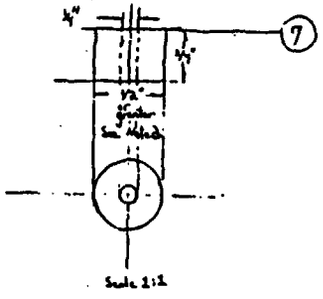


Installed Front View
Scale 1:2



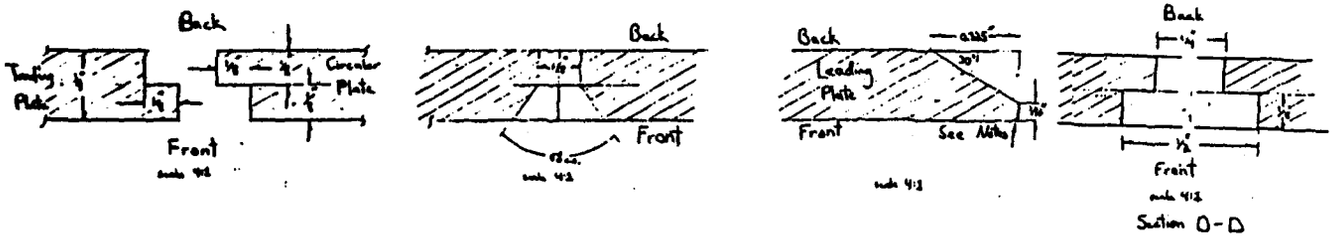
Scale 1:1

I - Beam Assembly
Top, Back and Side Views



Scale 1:1

Spacer Top, Front Views
See Note 2



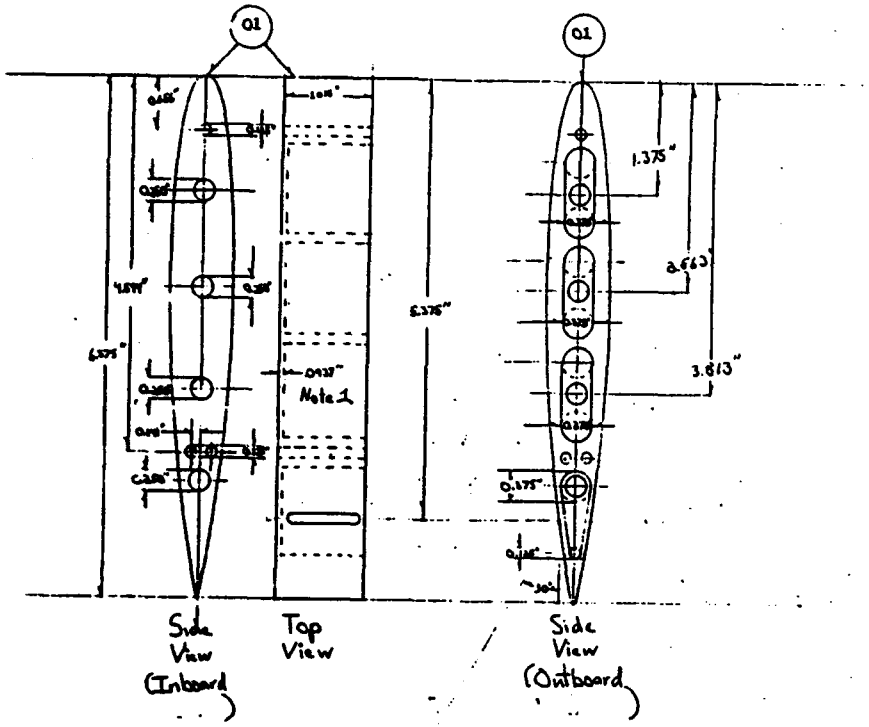
Section D-D

Note 1: The detail of Section C-C applies only to the leading edge of the leading plate.

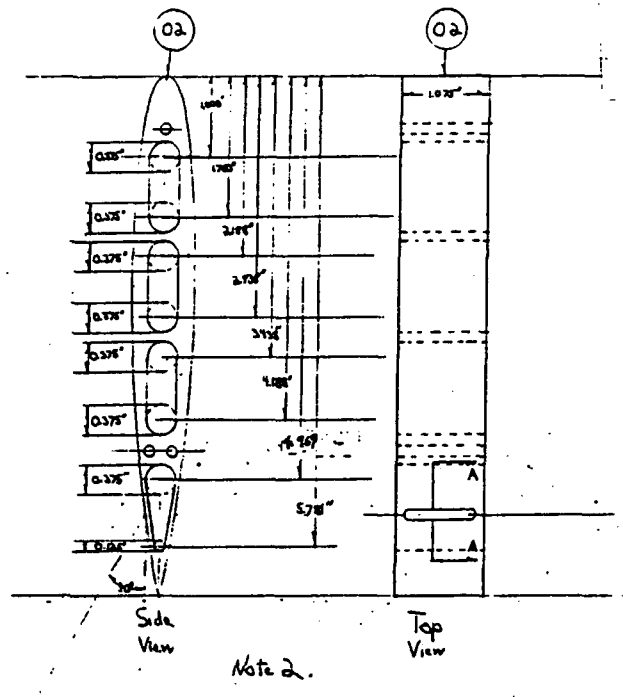
Note 2: Spacer outer diameter, shape undetermined.

Bill of Material

QTY	Part #	Part Name	Description
4	7	Spacers	Rubber or Aluminum Tubing
4	6	I-Beam Ends	Aluminum
2	5	I-Beam Body	Aluminum
2	4	Shims	Aluminum
1	3	Circular Plate	1/4" Plexiglas
1	2	Trailing Plate	1/4" Plexiglas
1	1	Leading Plate	1/4" Plexiglas



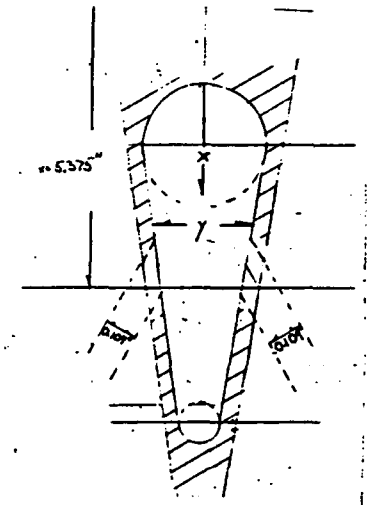
Scale 1:1



Note 2.

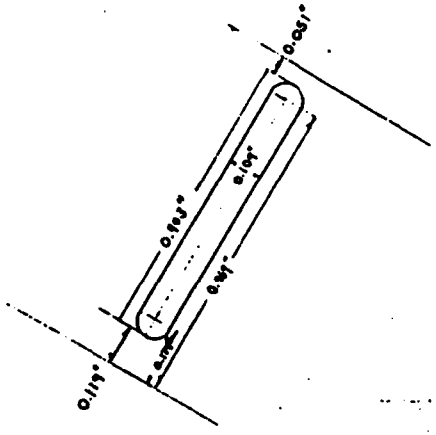
Scale 1:1

X	4.938"	5.360"	5.570"	5.781"
Y	0.375"	0.250"	0.188"	0.125"



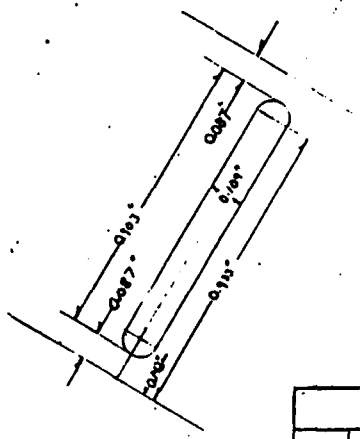
Detail A-A

Scale 4:1



Auxiliary View

Scale 4:1.



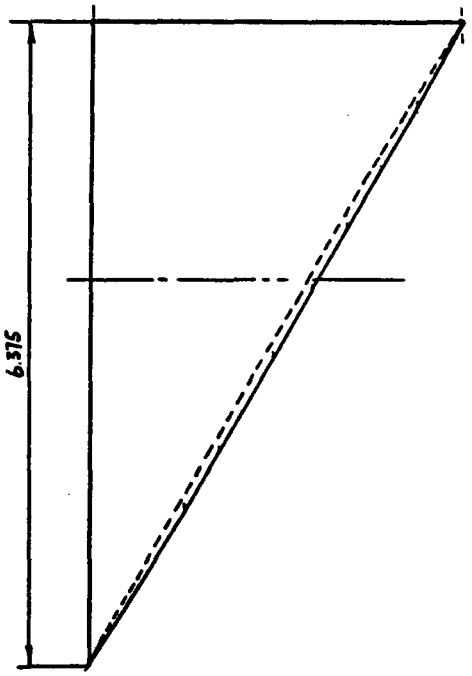
Auxiliary View

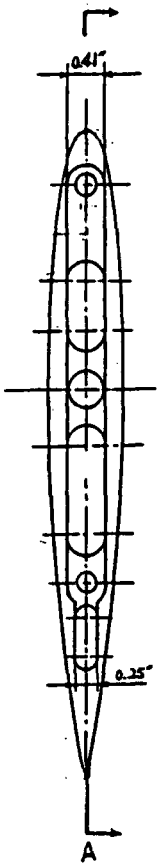
Scale 4:1

Note 1: The inboard wall of the inboard Type II tip has a thickness of 3/32" (0.0937")

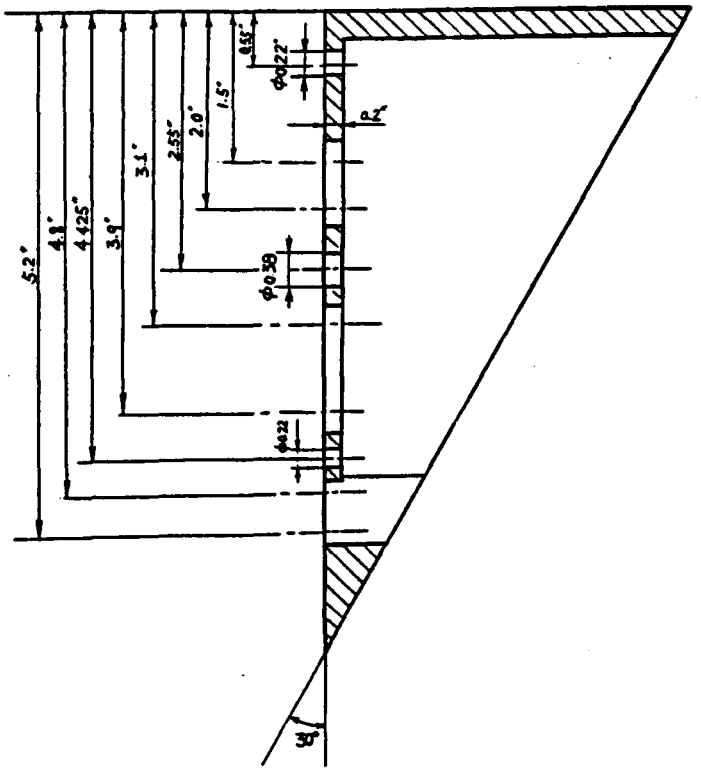
Note 2: The outboard Type II tip plumbing matches the plumbing of the outboard side of the inboard Type II tip. Both sides of the outboard tip are identical.

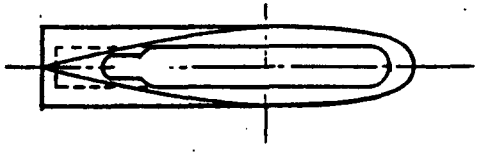
Bill of Material				Unswept Type II Tip		
QTY	Part #	Part Name	Description			
1	1	Inboard Tip II	Aluminum NACA 12-0040 material			
2	2	Outboard Tip II	Aluminum NACA 12-0040 material	07/19/89		Carlson 03





A-A View

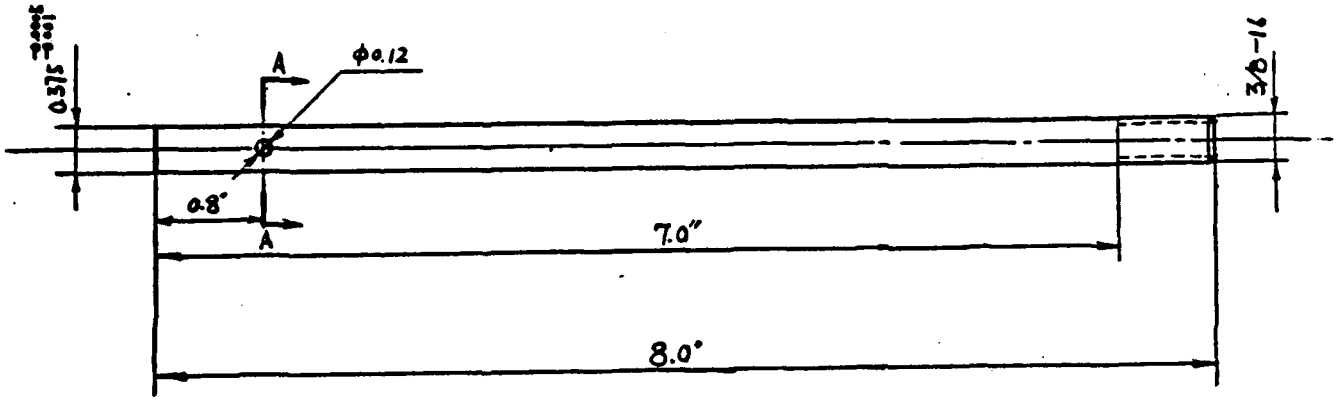


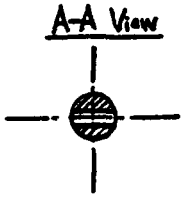


ERCI Back Sweep Model

Drawing No. 1

Piece: 1
Scale: 1:1
Material: Aluminum

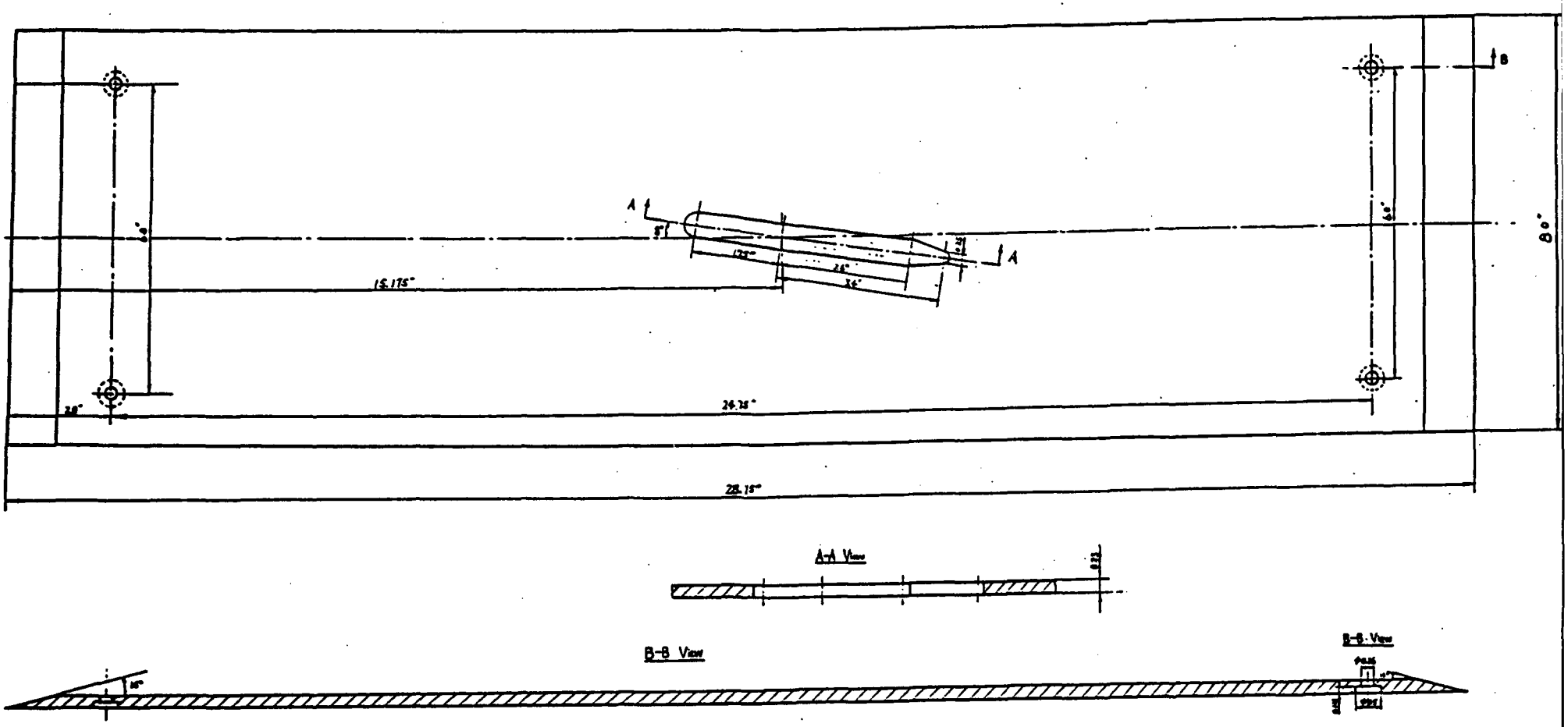




ERCI Back Sweep Model

Drawing No. 2

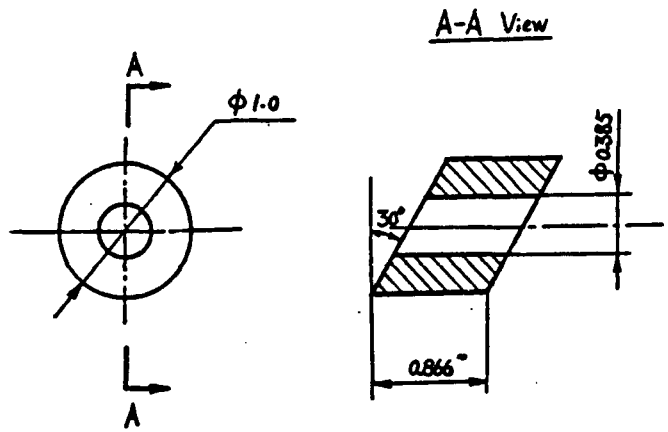
Piece: 1
Scale: 1:1
Material: Carbo-steel



ERCI Back Sweep Model

Drawing No. 3

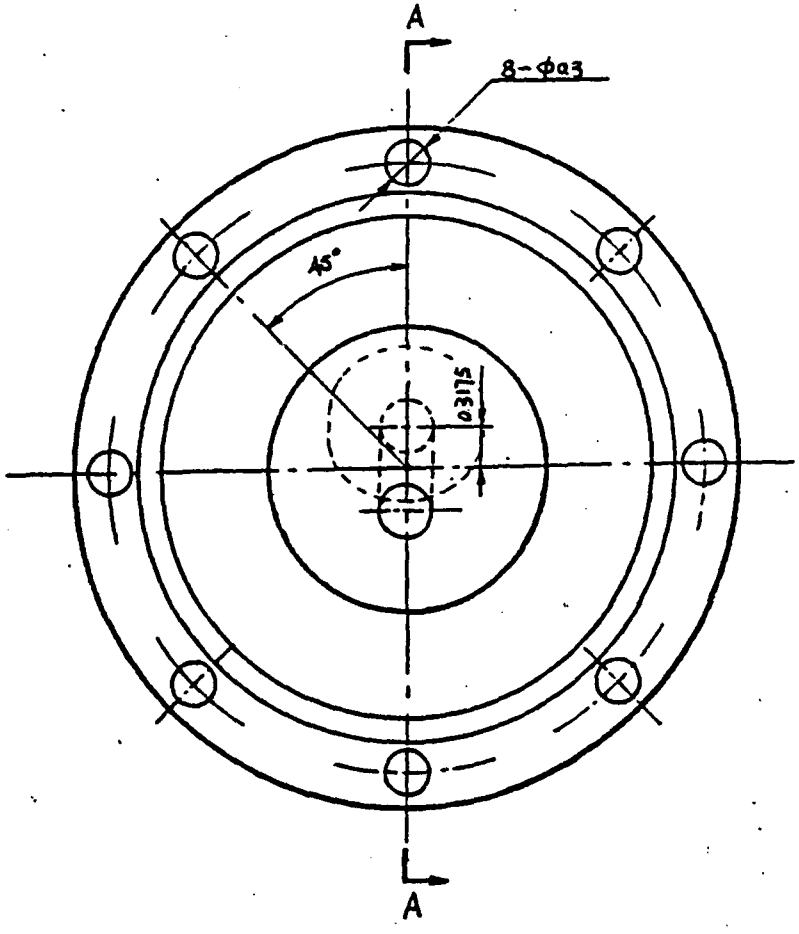
Piece: 1
Scale: 1:1
Material: Plastic Glass



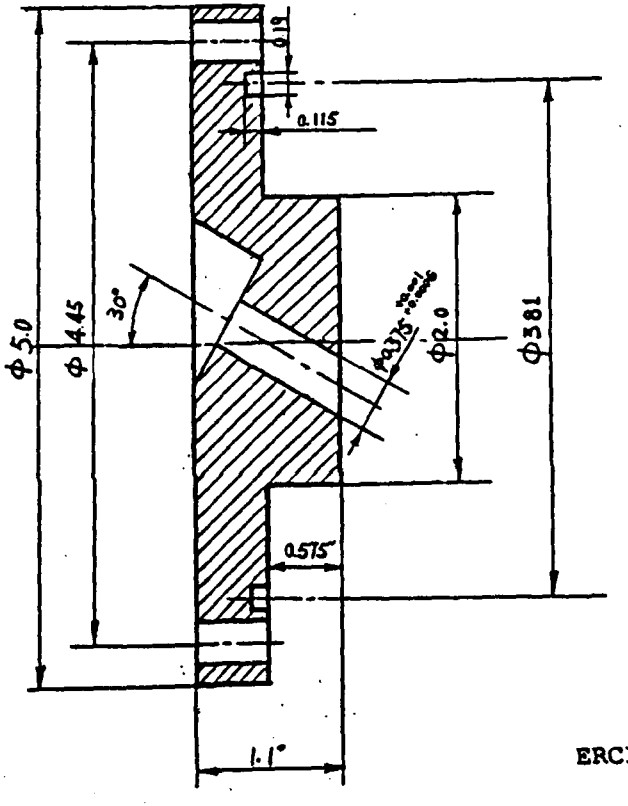
ERCI Back Sweep Model

Drawing No. 4

Piece: 1
Scale: 1:1
Material: Aluminum



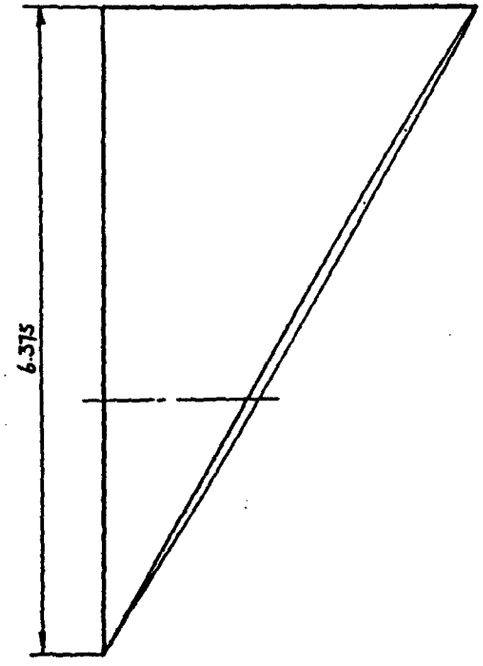
A-A View

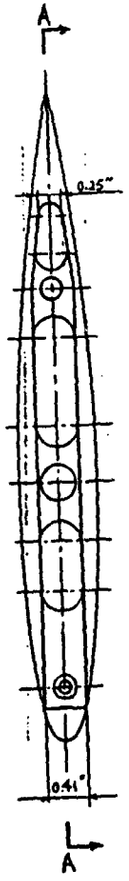


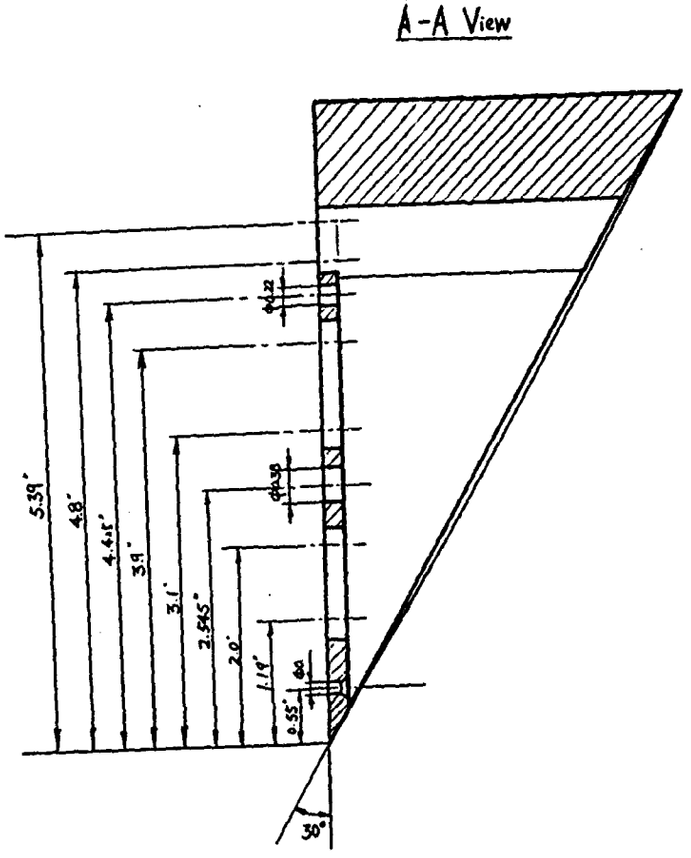
ERCI Back Sweep Model

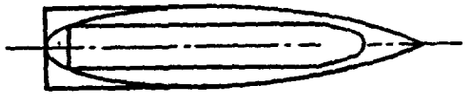
Drawing No. 5

Piece: 1
Scale: 1:1
Material: Aluminum





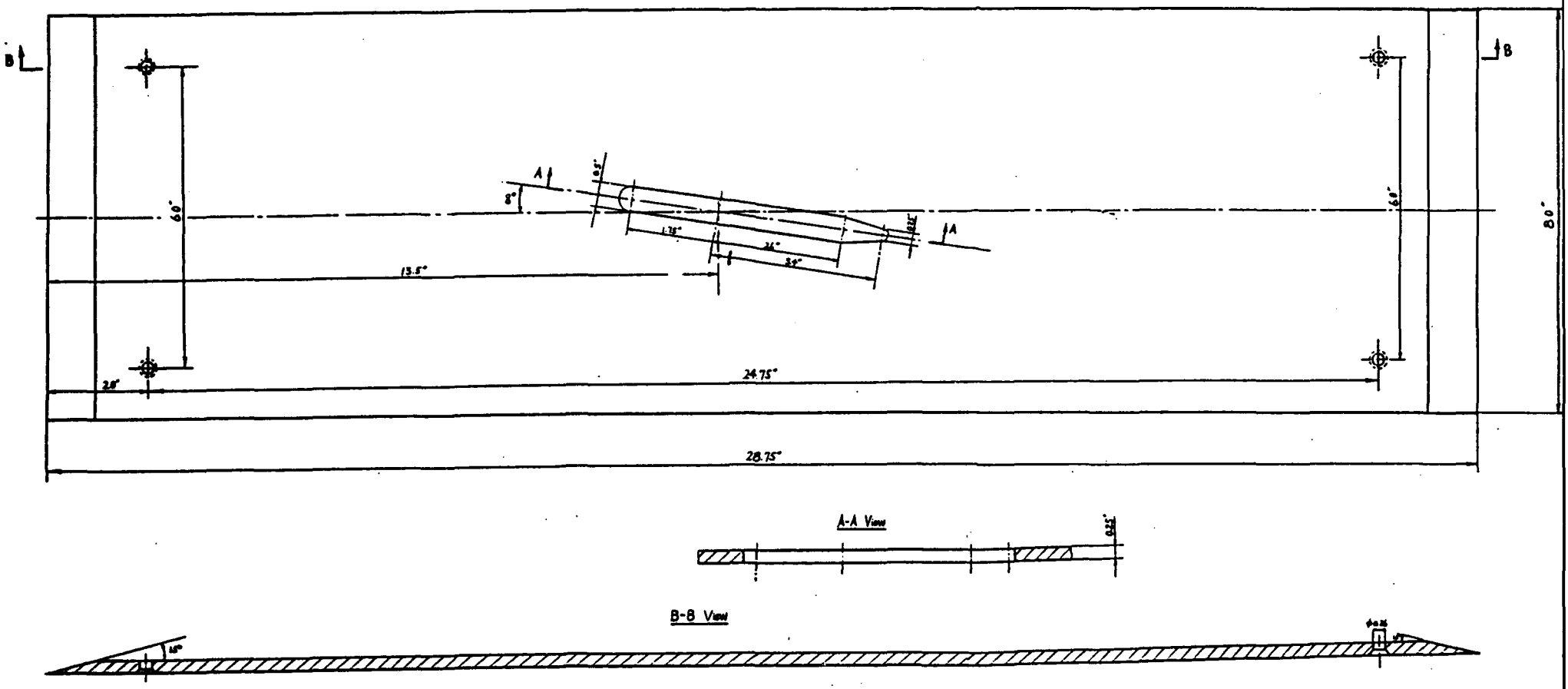




ERCI Forward Sweep Model

Drawing No. 1

Piece: 1
Scale: 1:1
Material: Aluminum



ERCI Forward Sweep Model

Drawing No. 2

Piece: 1
Scale: 1:1
Material: Plexiglas