NASA Technical Memorandum 102740

DESIGN AND FABRICATION OF INSTRUMENTED COMPOSITE AIRFOILS FOR A CRYOGENIC WIND TUNNEL MODEL

Clarence P. Young, Jr., George C. Firth,
William H. Hollingsworth, Jr.,
Bruce M. Adderholdt, and
Barry V. Gibbens

OCTOBER 1990

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

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SUMMARY

Two instrumented horizontal stabilizers and one instrumented vertical stabilizer have been designed and fabricated for testing on the Pathfinder I (PF-I) Transport Model in the NASA Langley Research Center National Transonic Facility (NTF). Two different designs were employed; the horizontal stabilizer utilized a metal spar and fiberglass overwrap and the vertical stabilizer was made of all fiberglass. All design requirements were met in terms of design loads, airfoil tolerances, surface finish, orifice hole quality, and proof-of-concept tests. Pressure tubing installation was found to be easier for these concepts as compared to methods used in conventional metallic models. Ease of repair was found to be a principal advantage in that some fabrication problems were overcome by reapplying fiberglass cloth and/or epoxy to damaged areas. Also, fabrication costs were judged to be lower when compared to the more conventional design fabrication costs.

INTRODUCTION

Full utilization of the high Reynolds Number capability provided by the NTF requires extension of the state-of-the-art in model design and fabrication. (See refs. 1 through 5.) Designers are faced with the challenge of developing new design concepts for models to be tested in the harsh, cryogenic temperature, high pressure environment associated with high Reynolds Number testing in the NTF. Inherent in the design and fabrication process is the need for minimizing fabrication costs of pressure models which have to meet very stringent requirements on airfoil tolerance, surface finish, and orifice hole quality.

Historically, fabrication of pressure instrumented models has been very difficult and costly due to complexity (refs. 2 and 6) and in many cases, models have been lost during fabrication, due to such causes as operator error or machine malfunction. In particular, more reliable and more cost effective methods for installing pressure tubes are needed. Based on experience at Langley Research Center with the use of composite materials for the NTF fan blades (E-glass/Epoxy) and aerodynamic testing of a 2-D composite airfoil in the 0.3-Meter Transonic Cryogenic Tunnel (TCT), it appeared that designs utilizing composite materials may have fabrication advantages over all metallic designs. Composite materials are routinely used for wind tunnel models as non-primary structural components, e.g., nose section or fuselage components (see ref. 1), and are heavily relied upon for aeroelastically tailored models (e.g., flutter models).

In most cases weight is not a design driver for large 3-D models. Metallic materials are used for both strength and stiffness. Stiffness is a principal driver for design of large lifting surfaces. However, large instrumented airfoils may not have sufficient stiffness when made entirely of glass reinforced plastics (GRP). This drawback may be overcome by using metal spars and/or high stiffness unidirectional advanced composites.

The purpose of this research was to demonstrate the feasibility of design and fabrication of NTF models and/or model components utilizing conventional and/or advanced composites. The potential payoffs were considered to be in the areas of fabrication technology improvement, ease of repair if damaged during fabrication or testing, and cost savings. It is envisioned that the next step beyond the present research effort will be to examine other design approaches (e.g., spar, rib, stringer construction) and to extend the technology to 3-D highly loaded model components.

DESIGN

General Requirements

The structural design requirements for the PF-I (see fig. 1) composite vertical and horizontal stabilizers are virtually identical to those for the original steel tails. The maximum aerodynamic loads that the horizontal and vertical stabilizers (figs. 2 and 3) will experience are 255 lbs. and 513 lbs., respectively.

Tolerances for the airfoil surface are specified to be $\pm.002$ inch with respect to the desired contour. A further requirement addressing waviness specifies that regardless of the specific value of a contour ordinate, the relative tolerance variation between adjacent ordinates shall not exceed .001 inch. The target surface finish for the model was 16 rms. These requirements are typical for testing instrumented airfoils at full scale Reynolds numbers and are more stringent than conventional models. It should be noted that research is currently being conducted to better define the surface finish requirements for high Reynolds number testing (see ref. 2). It is not clear that the present requirements being used for surface finish and tolerances over the entire surface are actually needed for many high Reynolds number models.

Each tail contains a total of 32 surface static pressure taps. For example, the horizontal stabilizer orifice locations were to be 33% and 67% of the exposed semi-span with one stabilizer having upper surface taps and the other having lower surface taps (see fig. 4). Orifices were to be .010 in. in diameter and be free of imperfections.

Concept

Due to the inherent problems in designing and fabricating cryogenic models, it is necessary to seek new approaches. Performing machining operations on a substrate expedites the pressure tubing installation while maintaining high quality orifices, results in major savings. In this concept, the use of a core, whether it was of steel or composite, with a cosmetic overwrap offered an opportunity to accomplish the fabrication tasks with less difficulty, lower risk, and without sacrificing the quality of the finished product.

Analysis

The stabilizers are designed to meet the structural criteria specified in LHB 1710.15 (ref. 8). The horizontal stabilizer design was driven by bending stress in the mounting attachment area (see fig. 5) where instrumentation passes through the airfoil surface into the mounting attachment. The shear stress that develops between the core and the fiberglass overwrap due to bending was found to be acceptable. The good comparability of the coefficients of thermal expansion between the 18 Ni Grade 200 Maraging steel core and the E-glass overwrap provides a stable, durable airfoil. The peak stress areas in the vertical tail include the bending stress in the mounting tangs (see fig. 6), and the shear stress between the core and the overwrap. Both airfoils were analyzed to assure freedom from flutter.

FABRICATION

Horizontal Stabilizer

The core of the horizontal tail is 18 Ni Grade 200 Maraging steel. The breechlock mounting attachment (fig. 5) used is identical to that used on the original all stainless steel horizontal tails. Consideration was originally given to using an E-glass/Epoxy core for this part. However, due to the complex geometry of the breechlock attachment and the complexity of composite fabrication techniques required to develop adequate strength, the decision was made to use a steel core instead. The steel airfoil core was machined 0.030 in. undersize and contained all tube grooves. After tubing installation (see fig. 7) the core was over-wrapped with approximately .080 in. thick E-glass. After curing, a final undersize contour was machined. Upon completion of final machining and hand polishing, (see fig. 8) the tail attachment was hand fitted to the fuselage (see fig. 9). The airfoil surface was then coated with a gel coat of resin which was approximately .002–.003 in. thick. Further handworking was completed, orifices drilled, and final validation of the airfoil shape and orifice locations was made.

Vertical Stabilizer

The fabrication process for the vertical stabilizer was very similar to that for the horizontal stabilizer. The core, however, is all composite E-glass material. The attachment to the fuselage is a simpler design (see fig. 6) which allowed for the use of traditional fabrication methods. The core was machined .030 in. undersize and tube grooves were cut in a manner similar to that used on the horizontal tail. After tubing installation, the tail was overwrapped with an .080 in. thickness of E-glass and cured (see fig. 10). The final oversize airfoil contour was machined and handworked. The mounting attachment was fitted into the fuselage and the airfoil surface was gel coated. After final polishing and orifice drilling, the airfoil shape and orifice locations were measured and documented. Stainless steel orifice tubing, .030 in. O.D. × .020 in. I.D., was used in both the horizontal and the vertical tail. Orifice openings .010 in. in diameter were drilled through the composite overwrap. Figure 11 illustrates both the horizontal and vertical tails fitted to the PF-I fuselage.

Special Procedures

Machining of tube grooves.- When machining the tube grooves, the following procedures should be followed:

1. The tube grooves must be accurate in size and location in order that the pressure taps intersect the finished surface at the prescribed locations.
2. Tube groove depths should be controlled such that no tube is allowed to protrude above the core surface in order to prevent damage to the tubes in the event the E-glass/Epoxy overwrap has to be removed from the core.
3. Tube groove width at the orifice hole locations should not vary greatly from the tube diameter. For example, a .040 in. diameter tube should have a groove width of no larger than .042 inches.
4. Checks should be made during and upon completion of tube installation to ensure that no tube protrudes above the core surface contour.
5. When tubes are secured by an adhesive, the adhesive should be confined to the tube groove such that it will not detract from visual distinction of the tube location after application of the composite (E-glass/Epoxy) overwrap. Good visual distinction allows very accurate location of the pressure taps.

Application of E-glass/Epoxy overwraps to steel and E-glass/Epoxy spars.- The spars (cores) should be prepared as follows:

1. Grit Blast
2. Clean with Methyl Ethyl Ketone (MEK)
3. Clean in Freon
4. Handle spars with clean room quality gloves to prevent contamination prior to being overwrapped and cured.

Machining of E-glass/Epoxy to finished contour.- The following procedure should be followed:

1. Machine surface contour with 1/2 in. diameter single flute carbide ball mill at approximately 2400 rpm at 15–20 in./sec.
2. Gaseous nitrogen is used as a coolant. Important- The gaseous nitrogen should be introduced at a slow rate in order to prevent (minimize) thermal shock that could crack resin in the E-glass system.
3. Material should be removed by making a roughing pass at a depth of .060 in. and the finish pass made at a depth of .017 in., leaving .003 in. above finish contour which is removed by hand finishing.

DISCUSSION OF FABRICATION EXPERIENCE

Extensive in-house experience has been obtained in the design and fabrication of model systems for testing at cryogenic temperatures in the NTF. Traditional methods do not fully address unique problems which most cryogenic models present. The tough, difficult to machine, cryogenic steel parts have both high material and fabrication costs. The more conventional installation of instrumentation presents difficulties, i.e., acceptable filler materials and surface finish, which in some cases has not met design requirements.

Concepts which use a core and whose surface can be built up using composite fabrication techniques offers a number of benefits. Instrumentation can be installed without concern for the eventual surface finish of the airfoil since an overwrap would be added later. Fabrication errors can be repaired locally or by full surface undercut because a new overwrap can be installed even if the model is in its final stages of fabrication when the error occurs. The potential for ruining a part is greatly diminished. Furthermore, the machining required for the core (steel or E-glass/Epoxy) can be performed to looser tolerances. The potential payoffs are savings in time and money required to complete the model. The use of an overwrap allows for orifice tubing to be located visually as well as numerically (using a validator) through the E-glass, thereby enabling the drilling of orifices to be done with greater confidence and accuracy.

Machining Characteristics of the E-glass/Epoxy Material

The following characteristics of the E-glass/Epoxy material offer machining advantages when compared to steel metallics:

a) Low tool pressure is required which reduces deflections in thin sections.

b) Material removal does not induce mechanical stresses which can cause distortion in metallic models.

c) Airfoils are dimensionally stable and can be machined very accurately.

Hand Finishing

The E-glass/Epoxy system is easy to hand finish. However, extreme caution must be exercised in finishing areas such as the leading and trailing edges because of quick material removal. Resin is squeegeed over the hand finished surface with a razorblade to improve surface finish.

The surface finish obtained on both the vertical and horizontal stabilizers ranged from 15 to 35 rms. This compares to a target value of 16 rms. The variation in surface finish is believed to be associated more with the inherent conditions i.e., structure of the layup, rather than the manner in which the surface is hand finished. Earlier experiences with a proof-of-concept specimen (ref. 4) utilizing the steel spar E-glass/Epoxy overwrap gave a better surface finish.

Drilling of Orifices

The pressure taps were drilled with .010 in. diameter high speed twist drills at 2000 to 2400 rpm. The ability to see through the fiberglass overwrap greatly reduces the instrumentation installation time and results in greater success in intersecting the tube. Figure 10 gives a close-up view of orifice holes which illustrate the differences between orifice holes judged to be "good" and "poor" quality in both the steel and E-glass/Epoxy surfaces. Chipping around the edge at the top of the hole was observed in some of the E-glass/Epoxy holes, and frayed glass was visible in some of the holes. This problem needs further study; however, it was observed that the quality of the pressure orifice(s) is related to the homogenity of the glass and resin (matrix). The 2-D E-glass/Epoxy composite airfoil tested in the 0.3 Meter TCT had much better quality orifices.

Cost Considerations

Although quantitative fabrication cost comparisons were not made between the composite tails and the all metal tails (not instrumented) for the PF-I, some qualitative comparisons can be made.

Based on the fabrication experience for this program, the overall fabrication cost savings for the metal spar design, when compared with a conventional all metal design using surface grooves for tube placement with filler materials, is estimated to be 50 percent. The estimated savings are attributed primarily to easier hand finishing to final contour, and easier location of pressure tubes for drilling orifice holes. Making the same comparison, the all composite E-glass/Epoxy design would result in greater cost savings. However, it should be pointed out that design cost will be higher for composite designs.

PROOF-OF-CONCEPT TESTING

Previous Testing of Similar Designs

Proof-of-concept and aerodynamic testing for similar airfoil designs has been done and reported in references 4 and 11. Both a steel core and E-glass core (grooved for instrumentation) with .030 in. thick E-glass overwrap were load tested.

The steel spar configuration discussed in reference 4 was designed to withstand the Pathfinder I wing loads. The steel core design was dynamically tested to three times the expected loads which developed a peak cyclic stress of 100 Ksi in the metal spar. The cyclic loads were applied at temperature ranges from room temperature to −300°F. The part performed well with no failures or evidence of fatigue damage from the high cyclic loads.

A two-dimensional airfoil with the E-glass/Epoxy core was aerodynamically tested in the NASA Langley 0.3 Meter Transonic Cryogenic Tunnel (TCT). The model's performance was excellent. The aerodynamic data compared very well with an all metal airfoil of the same geometry that had been previously tested in the TCT. These tests proved the feasibility of using the all fiberglass core with overwrap for 2-D models for testing in a cryogenic environment. The research results are presented in reference 11.

Horizontal Stabilizer Load Tests

Although previous testing of concepts very much similar to the composite tails did not reveal a problem, limited proof-of-concept tests were performed for the horizontal tail. In view of the acceptably low working stress, materials compatibility, and proven wind tunnel experience for the E-glass/Epoxy core design concept no load testing was conducted on the vertical stabilizer.

The horizontal stabilizer was loaded to three times the expected aerodynamic loads at a temperature of −300°F for 5 cycles. The tail was subjected to nondestructive examination before and after the load tests. No evidence of structural damage or change in dimensions was found.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study led to the following conclusions:

1. Two instrumented composite airfoil concepts were designed and fabricated and one was structurally tested to three times the expected load. Both utilize a solid spar of either steel or fiberglass (E-glass/Epoxy) with a fiberglass skin overwrap.
2. The use of conventional and/or advanced composites for instrumented airfoils to be tested at high Reynolds number in a cryogenic environment is quite feasible.
3. The principal fabrication advantages afforded by these concepts when compared to conventional design are:
   a) Models can be more easily recovered from damage during fabrication.
   b) Location and drilling of orifices is much easier when compared to conventional designs.
   c) The airfoils are much easier to work to final contour.
   d) The airfoils have excellent dimensional stability during machining and cryo cycling.
4. The major fabrication difficulties encountered were:
   a) Very smooth surface finishes (≈16 rms) are more difficult to achieve with fiberglass than with all metal airfoils.
   b) Orifice hole quality was less than desired and needs to be improved.

5. Significant fabrication cost savings can be achieved. Based on this limited experience it is estimated that an overall cost savings of approximately 50 percent is achievable for the metal spar design when compared to all metal conventional airfoils. An even greater fabrication cost savings can be achieved for the E-glass/Epoxy design.

The results of the study are encouraging and it is recommended that these concepts be considered for 2-D and 3-D airfoils. The application to large lifting surfaces where deflection is critical will more than likely require the use of a steel spar. Further work needs to be done in the areas of improvement in surface finish and orifice hole quality.

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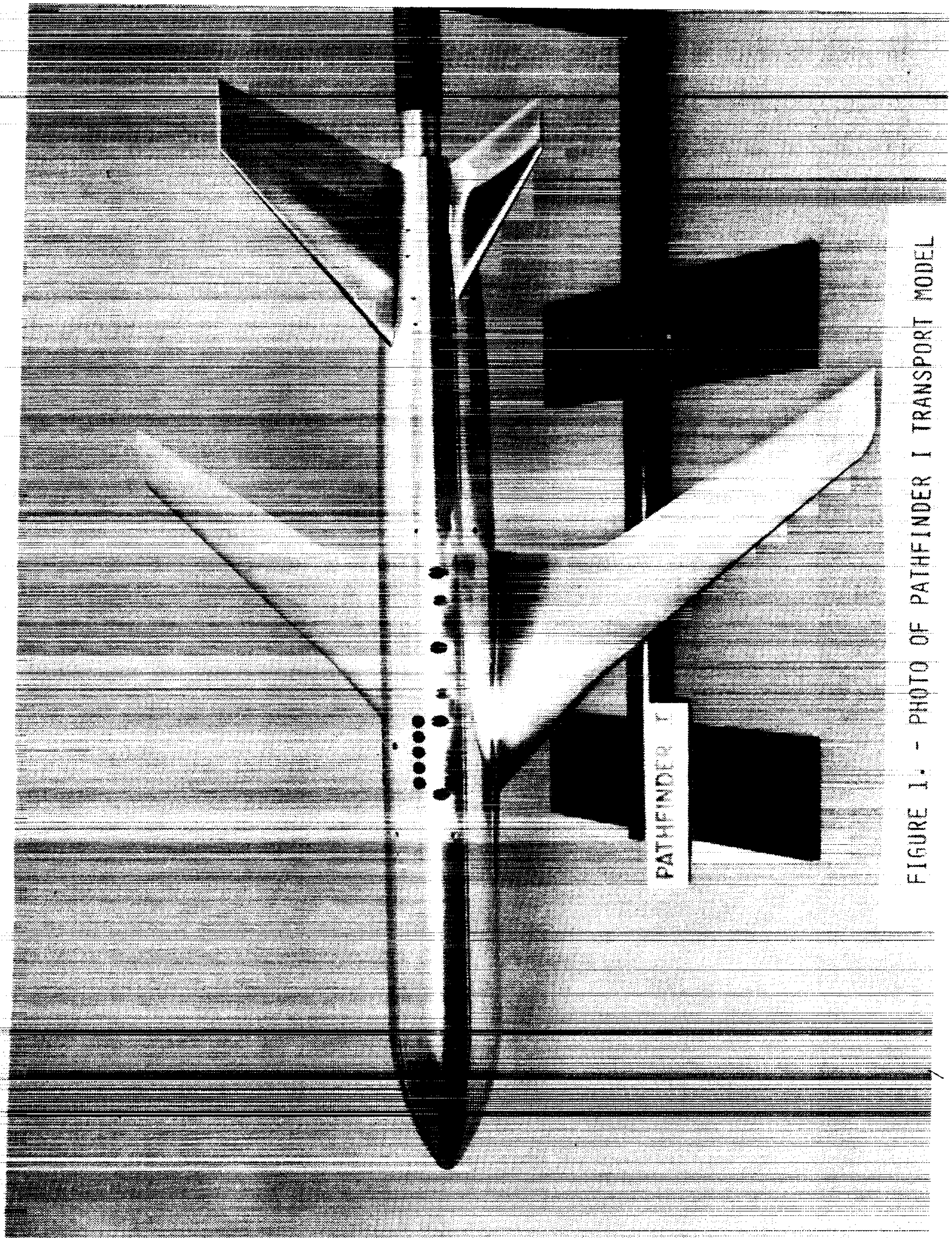

FIGURE 1. - PHOTO OF PATHFINDER I TRANSPORT MODEL

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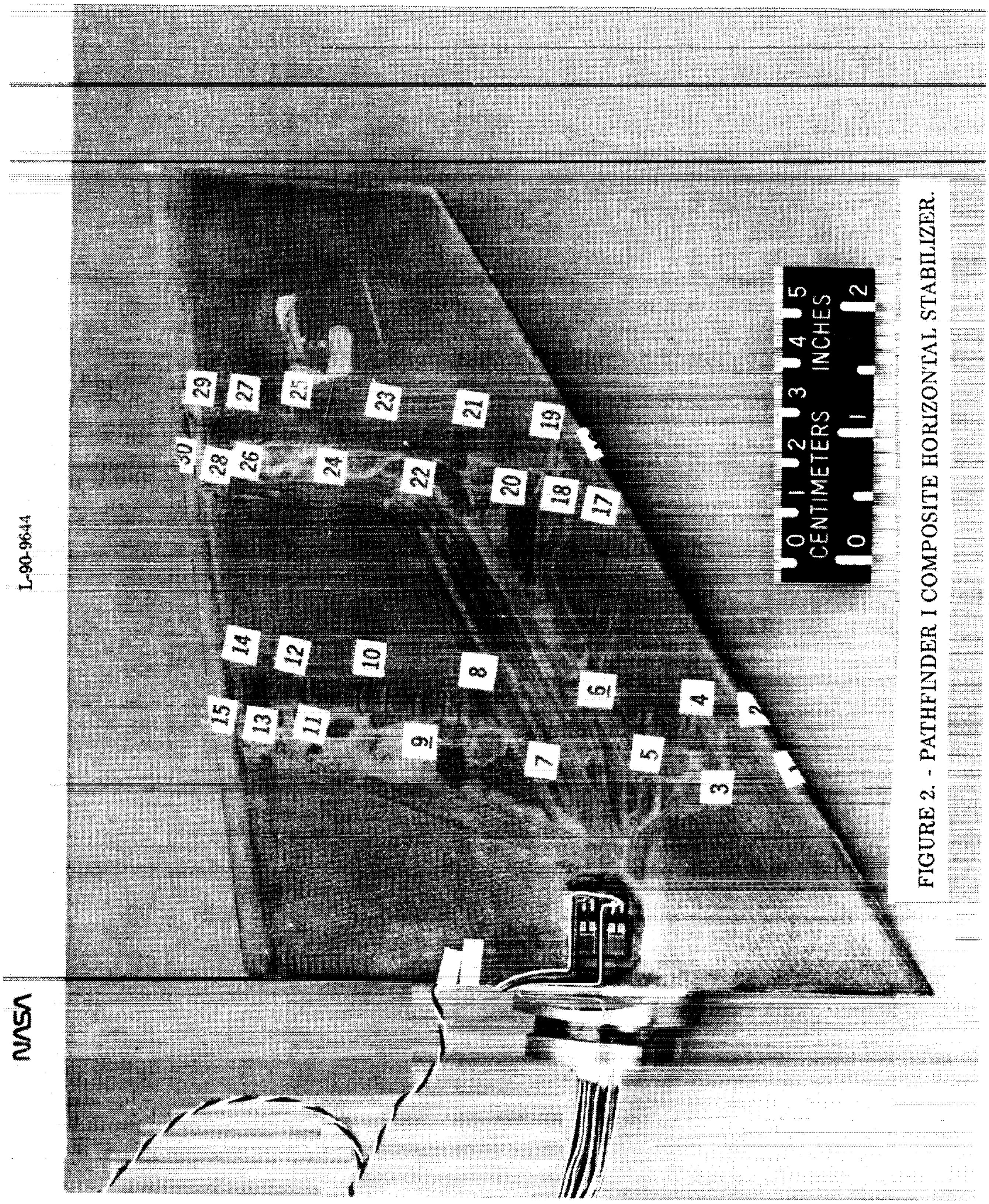

FIGURE 2. - PATHFINDER I COMPOSITE HORIZONTAL STABILIZER.

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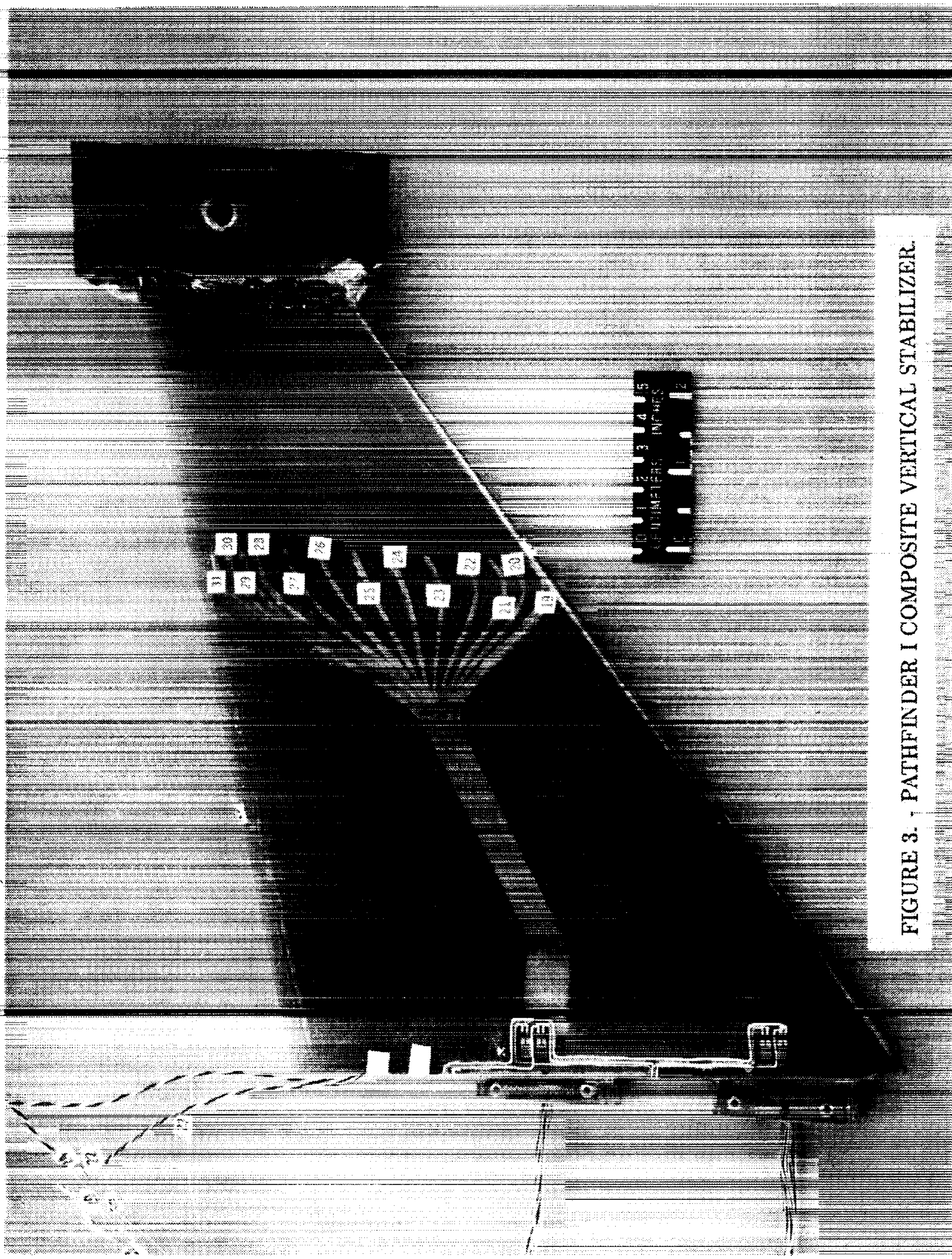

FIGURE 3. - PATHFINDER I COMPOSITE VERTICAL STABILIZER.

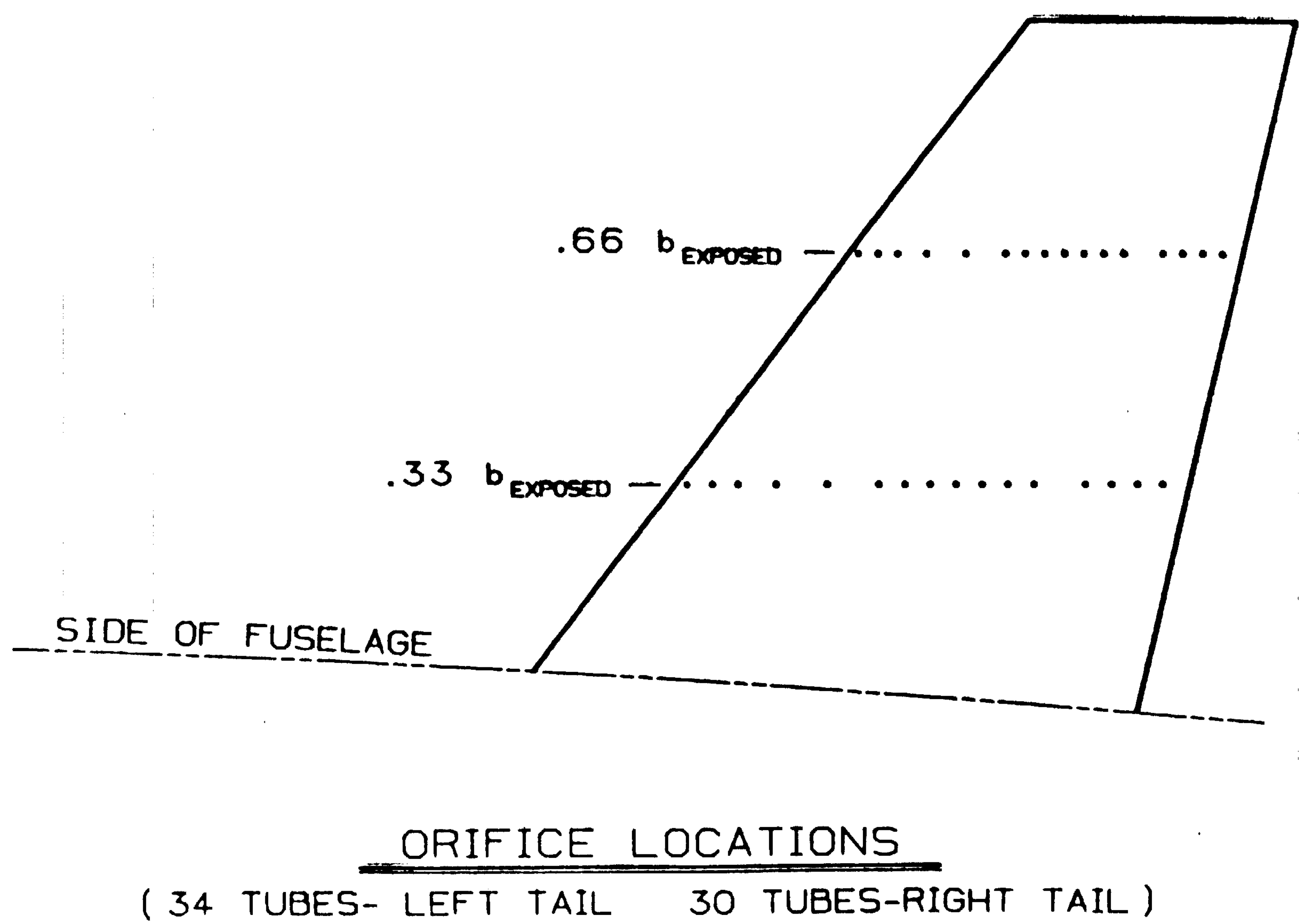

FIGURE 4. - LOCATION OF ORIFICES ON HORIZONTAL STABILIZER.

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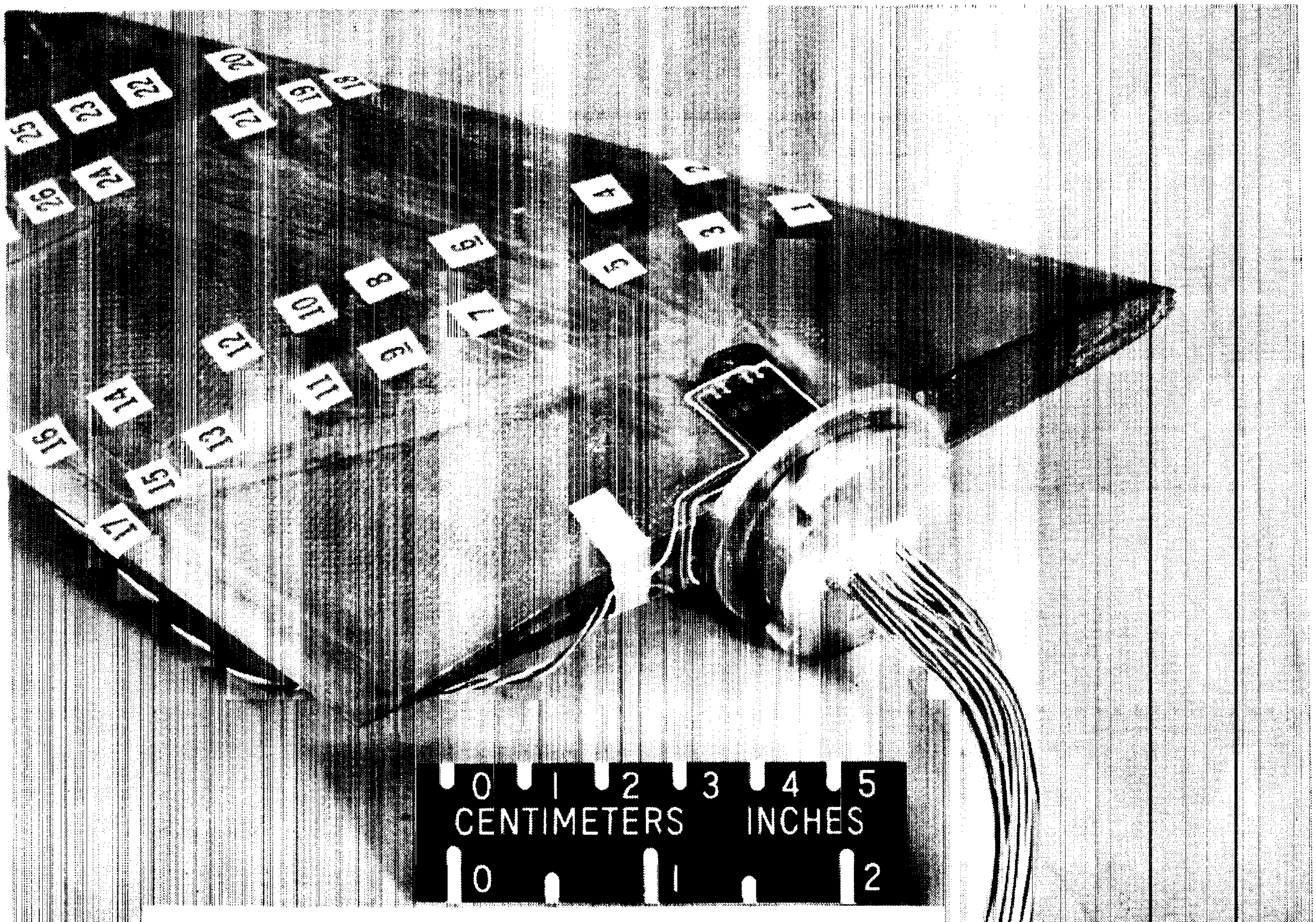

FIGURE 5. - PATHFINDER I HORIZONTAL STABILIZER ILLUSTRATING BREECHLOCK MOUNTING ATTACHMENT.

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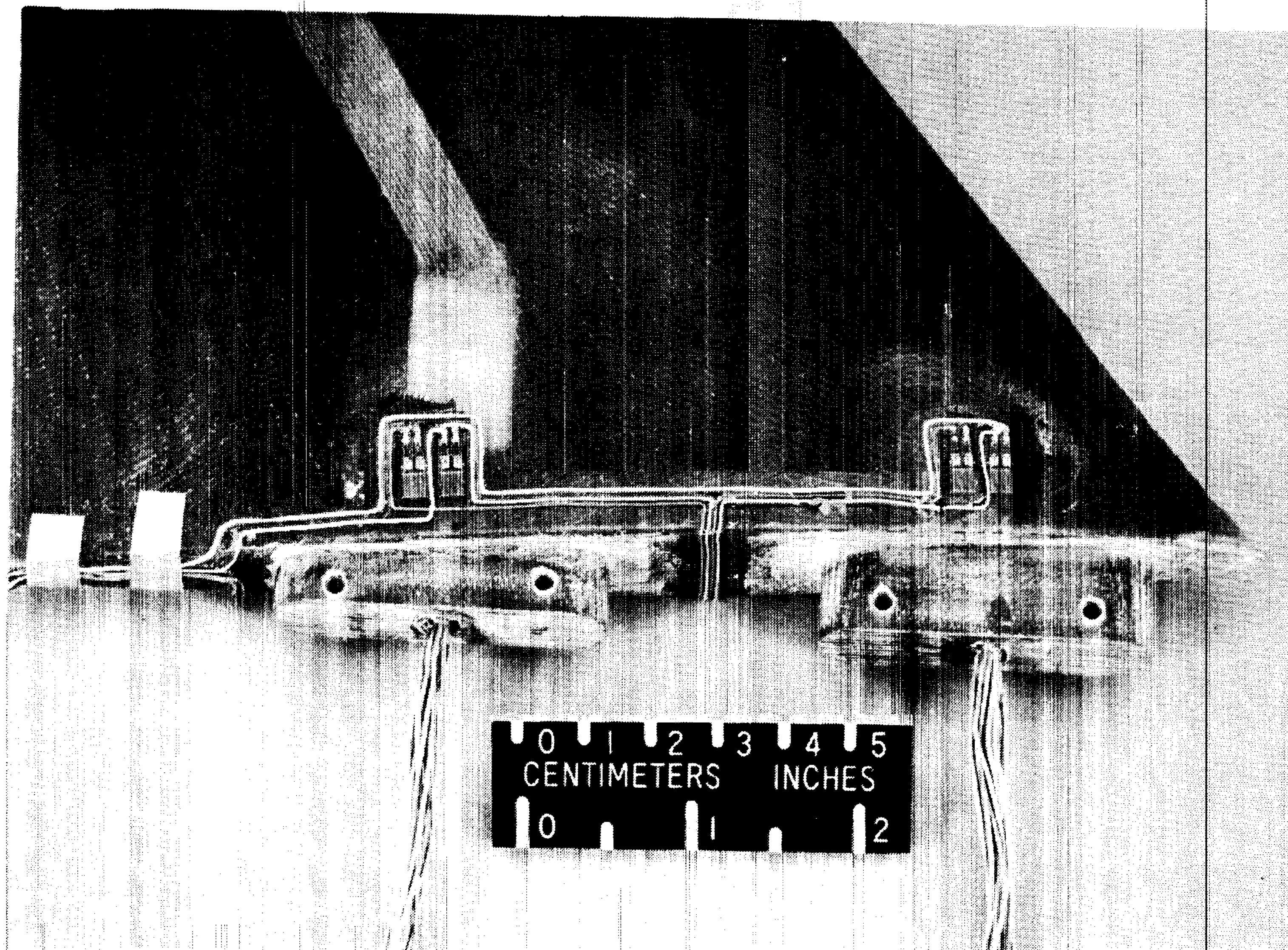

FIGURE 6. - PATHFINDER I VERTICAL STABILIZER ILLUSTRATING ATTACHMENT TANGS.

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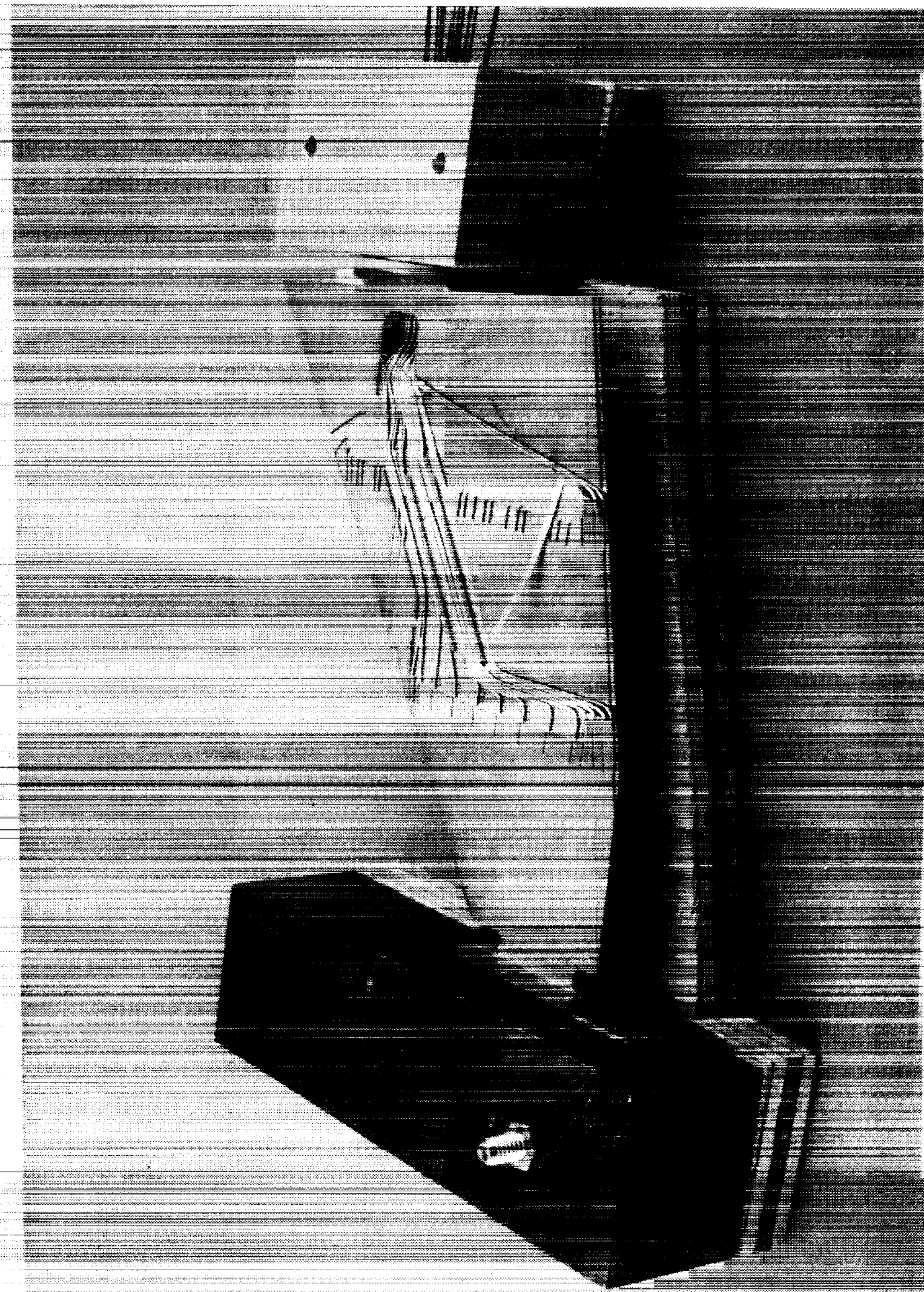

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FIGURE 7. - HORIZONTAL STABILIZER METAL SPAR WITH TUBES INSTALLED IN GROOVES.

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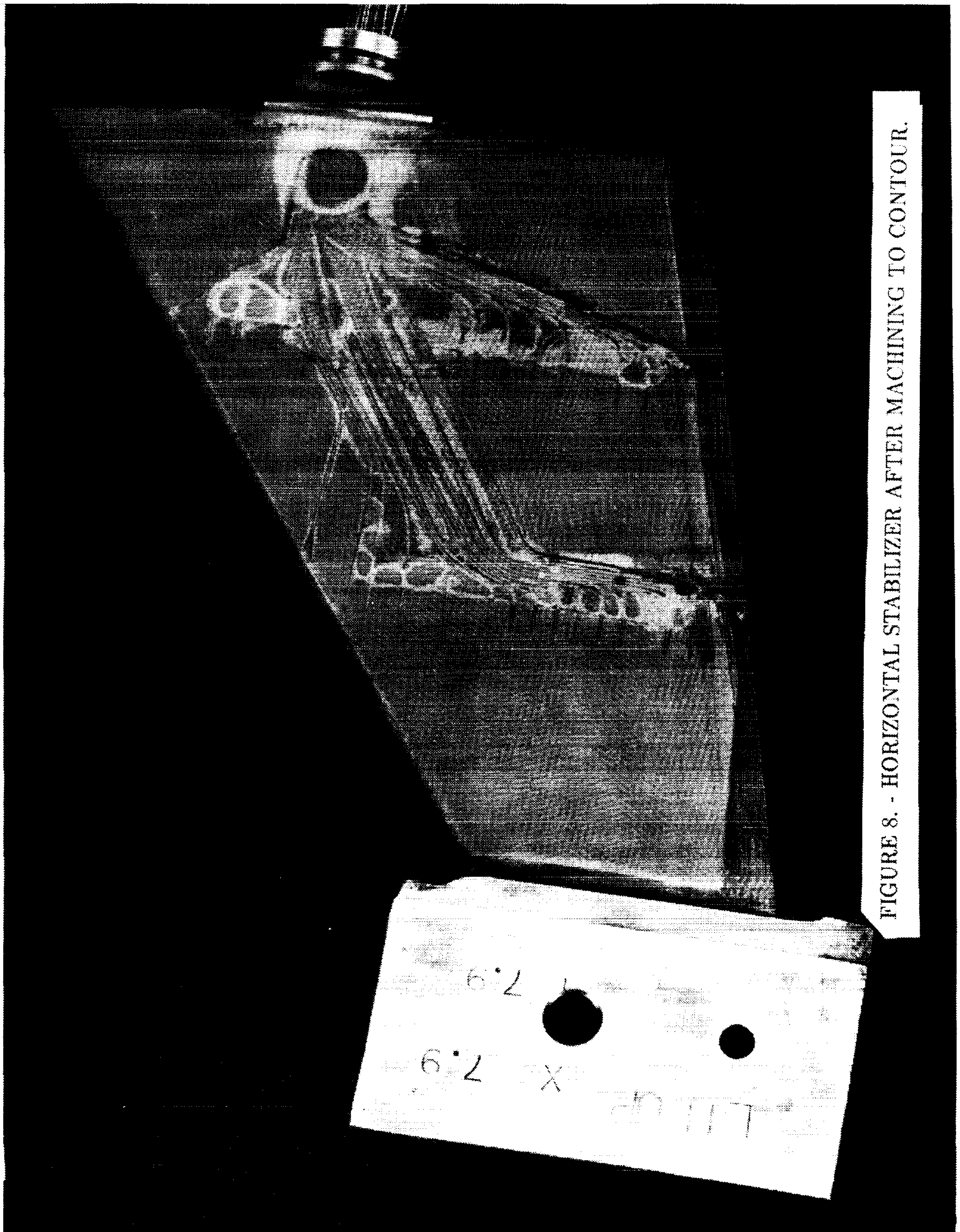

FIGURE 8. - HORIZONTAL STABILIZER AFTER MACHINING TO CONTOUR.

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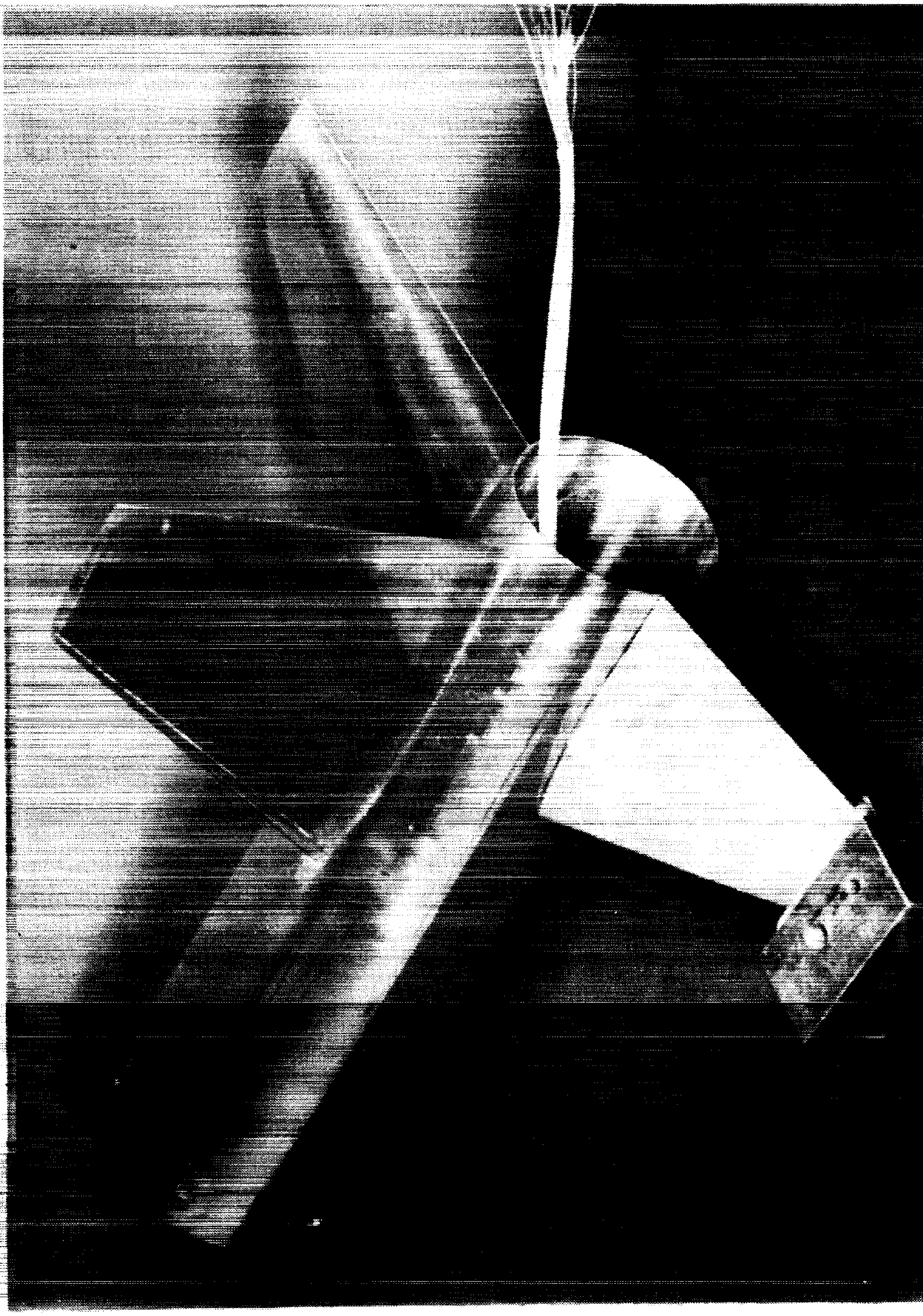

FIGURE 9. - LEFT HORIZONTAL STABILIZER FITTED TO PATHFINDER I FUSELAGE.

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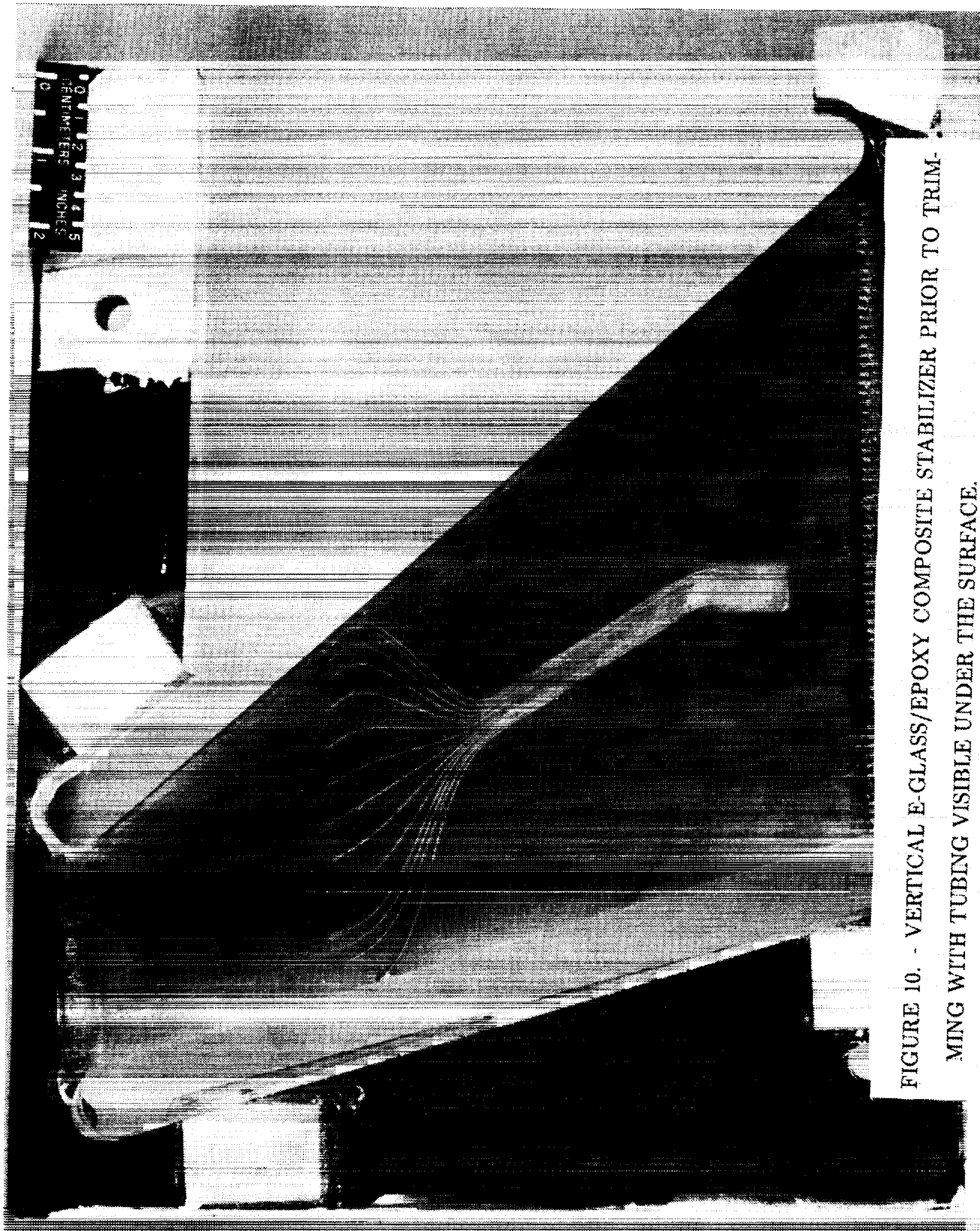

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FIGURE 10. - VERTICAL E-GLASS/EPOXY COMPOSITE STABILIZER PRIOR TO TRIMMING WITH TUBING VISIBLE UNDER THE SURFACE.

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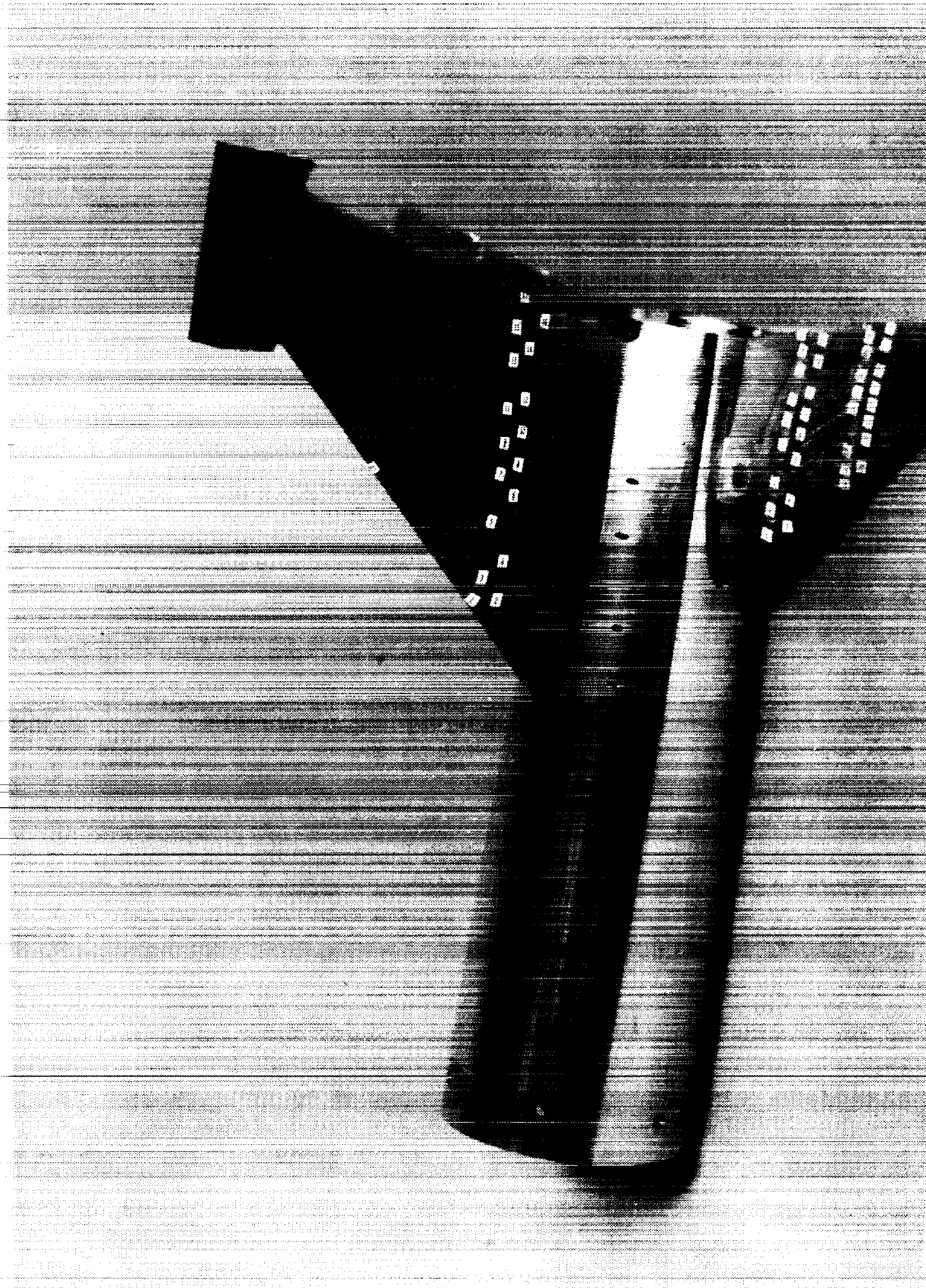

FIGURE 11. - COMPOSITE HORIZONTAL AND VERTICAL STABILIZER FITTED TO PATHFINDER I FUSELAGE.

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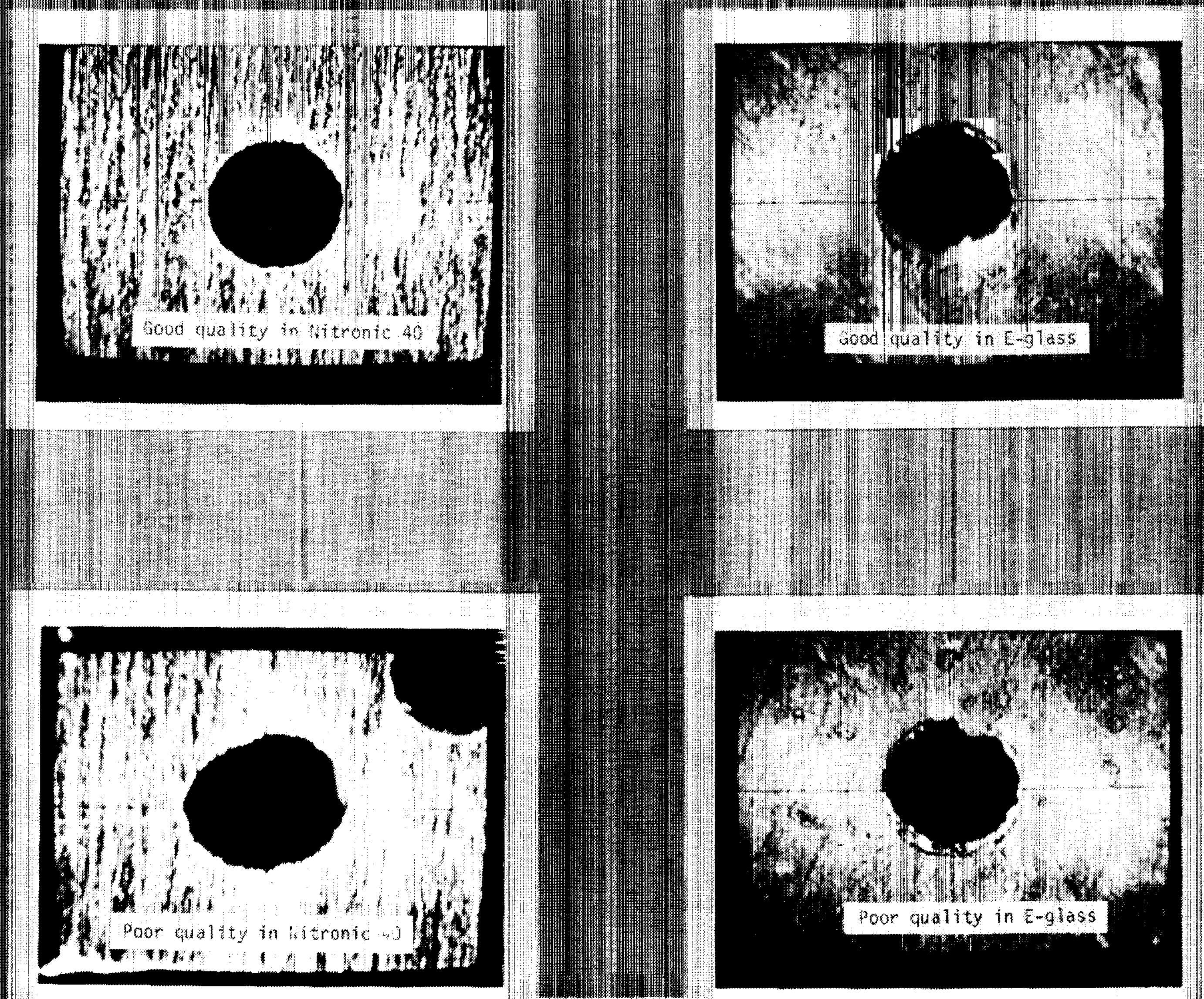

FIGURE 12. - ILLUSTRATION OF "GOOD" AND "POOR" QUALITY ORIFICES IN STEEL (NITRONIC 40) AND E-GLASS/EPOXY.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102740		

4. Title and Subtitle

Design and Fabrication of Instrumented Composite Airfoils for a Cryogenic Wind Tunnel Model

5. Report Date

October 1990

6. Performing Organization Code

7. Author(s)

Clarence P. Young, Jr., George C. Firth, William H. Hollingsworth, Bruce M. Adderholdt, and Barry V. Gibbens

8. Performing Organization Report No.

10. Work Unit No.

505-61-85-01

9. Performing Organization Name and Address

NASA Langley Research Center
Hampton, Virginia 23665-5225

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes

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17. Key Words (Suggested by Author(s))

composite structures
instrumented airfoils
wind tunnel models
composite fabrication

18. Distribution Statement

unclassified - unlimited

subject category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
unclassified	unclassified	28	A03

NASA FORM 1626 OCT 86