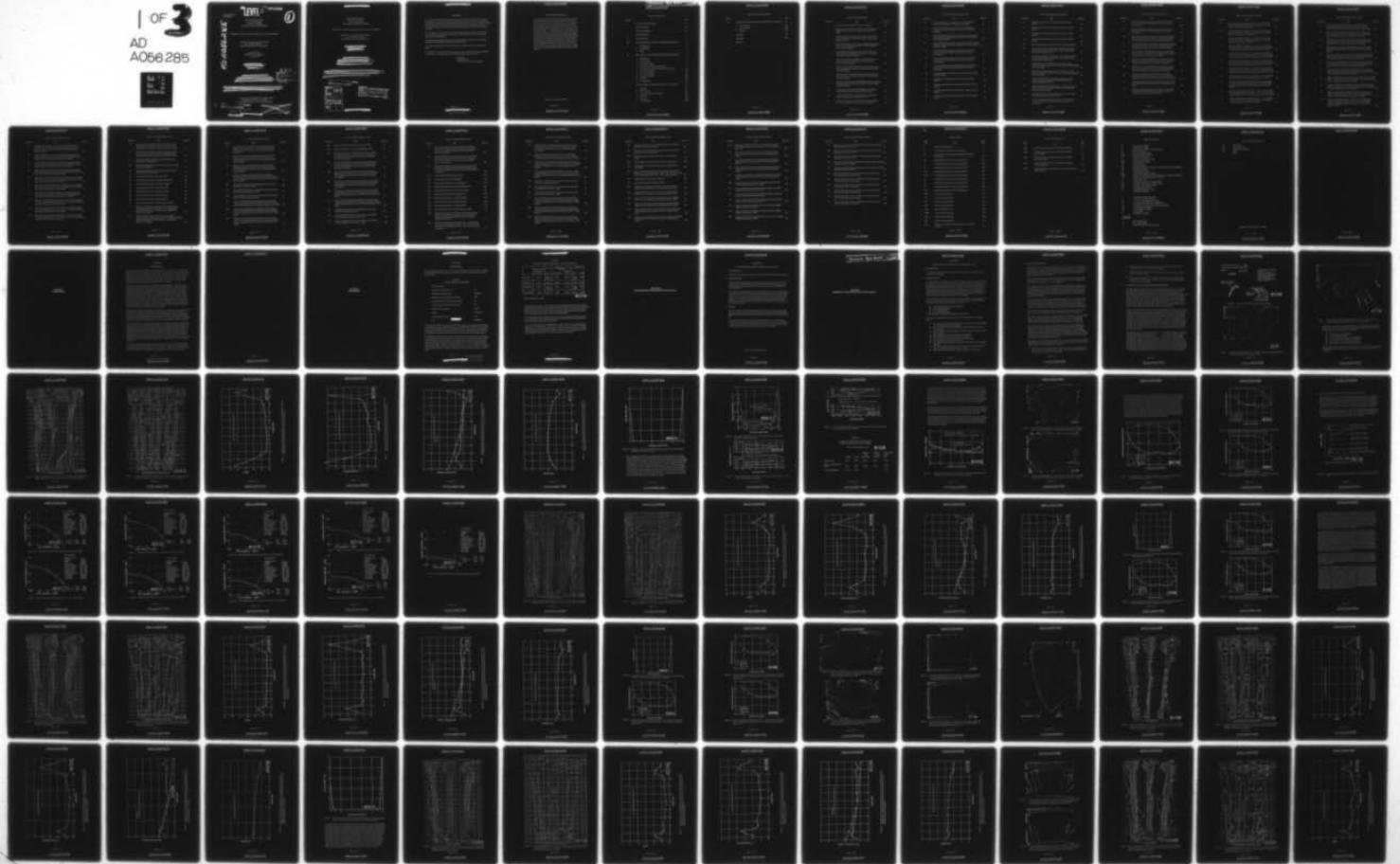


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AFAPL-TR-69-92  
VOLUME IV

**AD-A056285**

(UNCLASSIFIED TITLE)  
INVESTIGATION OF  
A HIGHLY LOADED  
TWO-STAGE FAN-DRIVE TURBINE

VOLUME IV. Phase II, End Wall Boundary Layer Control Evaluation

H. Welna, D. E. Dahlberg and W. H. Heiser  
Pratt & Whitney Aircraft  
Division of United Aircraft Corporation

Technical Report  
AFAPL-TR-69-92 Volume IV  
December 1969

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## FOREWORD

(U) This Interim Technical Status Report (Contractors Reference No. PWA 3827) was prepared by Pratt & Whitney Aircraft, Division of United Aircraft Corporation, East Hartford, Connecticut, as the fourth Semiannual Report under United States Air Force Contract F33615-68-C-1208, Project No. 3066, Task No. 306606. This report was submitted by the Contractor on 31 December 1969, and covers the report period from 1 July 1969 to 31 December 1969.

(U) The findings and conclusions of this report are not deemed as final by the Contractor. They are subject to verification or revision in the Final Report to be published upon the completion of this Contract.

(U) The Air Force Program Monitor is Mr. Wayne Tall, APTC, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, 45433.

(U) This report contains no Classified information extracted from other Classified documents.

(U) Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Wayne Tall  
Project Engineer  
Air Force Aero Propulsion Laboratory

PAGE NO. ii

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**UNCLASSIFIED ABSTRACT**

(U) A comprehensive, four-phase, three-year program is in progress to investigate methods of improving the performance of fan-drive turbines. The goals of this program are to develop turbine design procedures and aerodynamic techniques for high work, efficient, low-pressure turbines. The first phase effort of defining the preliminary turbine design has been completed and the results were reported (Reference 1). The second phase consists of an experimental evaluation which includes establishment of both two-dimensional loss levels and three-dimensional flow behavior for the baseline airfoils and for airfoils utilizing various boundary layer control methods. The design of the baseline cascade packs was reported in the Reference 2 Report, and the three-dimensional performance of the baseline airfoils was reported in the Reference 3 Report. The test results of the baseline airfoil boundary layer control methods and the performance of the decreased solidity annular cascades are presented in this report.

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PAGE NO. iii

**UNCLASSIFIED**

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TABLE OF CONTENTS

| Section |  | Page  |
|---------|--|-------|
|         | LIST OF ILLUSTRATIONS                                | vii   |
|         | LIST OF TABLES                                       | xxiii |
|         | LIST OF SYMBOLS                                      | xxv   |
| I       | INTRODUCTION   | 1     |
| II      | BACKGROUND   | 3     |
| III     | TWO-DIMENSIONAL DESIGN VERIFICATION (TASK IIa)       | 5     |
|         | 1. RFP Objective                                     | 5     |
|         | 2. Task Objective                                    | 5     |
|         | 3. Status  | 5     |
| IV      | BOUNDARY LAYER CONTROL EVALUATION (TASK IIc)         | 7     |
|         | 1. RFP Objective                                     | 7     |
|         | 2. Task Objective                                    | 7     |
|         | 3. Cascade Pack Design                               | 8     |
|         | 4. Flow Fence and Increased Roughness                | 9     |
|         | 5. Baseline Retest with Redesigned Inlet Guide Vanes | 25    |
|         | 6. Recontoured Airfoil                               | 74    |
|         | 7. End Wall Contouring                               | 91    |
|         | 8. Recambered Airfoil                                | 104   |
|         | 9. Summary   | 120   |
|         | 10. Test Procedure                                   | 122   |
| V       | MEDIUM SOLIDITY AIRFOIL EVALUATION (TASK II d)       | 123   |
|         | 1. Objective   | 123   |
|         | 2. Task Objective                                    | 123   |
|         | 3. Cascade Pack and Facility Design                  | 123   |
|         | 4. Discussion  | 133   |
|         | 5. Summary   | 160   |
|         | 6. Test Procedure                                    | 160   |

# UNCLASSIFIED

## TABLE OF CONTENTS (Cont'd)

| Section |  | Page |
|---------|--|------|
| VI      | PRELIMINARY DESIGN MANUAL PREPARATION (TASK IIe) | 163  |
|         | 1. RFP Objective                                 | 163  |
|         | 2. Task Objective                                | 163  |
|         | 3. Status  | 163  |
|         | Appendix   | 165  |
|         | References                                       | 183  |
|         | DD 1473  |      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 1          | Second Vane O. D. Shroud Flow Fence Installation  | 10       |
| 2          | Oil and Graphite Flow Patterns--Second Vane with View of Outside Diameter Flow Fences; Midspan Exit Mach No. = 0.903                          | 10       |
| 3          | Oil and Graphite Flow Patterns--Second Vane with View of Inside Diameter Increased Surface Roughness; Midspan Exit Mach No. = 0.903           | 11       |
| 4          | Pressure Loss Contours, Second Vane--Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.903, O.D. Flow Fences and I.D. Roughness  | 12       |
| 5          | Exit Gas Angle Contours, Second Vane--Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.903, O.D. Flow Fences and I.D. Roughness | 13       |
| 6          | Spanwise Pressure Loss Distribution, Second Vane--Screen Removed, Midspan Exit Mach No. = 0.903, O.D. Flow Fences and I.D. Roughness          | 14       |
| 7          | Spanwise Loss Coefficient Distribution, Second Vane--Screen Removed, Midspan Exit Mach No. = 0.903, O.D. Flow Fences and I.D. Roughness       | 15       |
| 8          | Spanwise Exit Gas Angle Distribution, Second Vane--Screen Removed, Midspan Exit Mach No. = 0.903, O.D. Flow Fences and I.D. Roughness         | 16       |
| 9          | Spanwise Exit Mach Number Distribution, Second Vane--Screen Removed, Midspan Exit Mach No. = 0.903 O.D. Flow Fences and I.D. Roughness        | 17       |
| 10         | Inlet Duct Loss Versus Percent Radial Span--Second Vane Cascade With I.D. Roughness and O.D. Flow Fences                                      | 18       |
| 11         | Comparison of O.D. Flow Fence and I.D. Roughness Loss Coefficient Distribution with Baseline Values   | 19       |
| 12         | Effect of Mach Number on Profile Loss Coefficient for O.D. Flow Fence and I.D. Increased Roughness Evaluation                                 | 19       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 13         | Effect of Mach Number on Profile Loss Coefficient for O.D. Flow Fence and I.D. Increased Roughness Evaluation                                  | 20       |
| 14         | Comparison of Spanwise Averaged Exit Gas Angle Baseline Distribution and Angles; Measured with Flow Fences/Surface Roughness                   | 21       |
| 15         | Oil and Graphite Flow Patterns—Second Vane with View of Both Flow Fence and Increased Surface Roughness Effects; Midspan Exit Mach No. = 0.903 | 22       |
| 16         | Oil and Graphite Flow Patterns—Second Vane with View of Both Flow Fence and Increased Surface Roughness Effects; Midspan Exit Mach No. = 0.903 | 22       |
| 17         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences—Root Section                | 23       |
| 18         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences—Mean Section                | 24       |
| 19         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences—Tip Section                 | 24       |
| 20         | Elevation and Section Location of the Redesigned Second Vane Inlet Guide Vane  | 25       |
| 21         | Redesigned Inlet Guide Vane, Second Vane Cascade, Root Section   | 26       |
| 22         | Redesigned Inlet Guide Vane, Second Vane Cascade, 1/8 Root Section   | 26       |
| 23         | Redesigned Inlet Guide Vane, Second Vane Cascade, 1/4 Root Section   | 27       |
| 24         | Redesigned Inlet Guide Vane, Second Vane Cascade, 3/8 Root Section   | 27       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 25         | Redesigned Inlet Guide Vane, Second Vane Cascade, Mean Section  | 28       |
| 26         | Redesigned Inlet Guide Vane, Second Vane Cascade, 1/8 Tip Section   | 28       |
| 27         | Redesigned Inlet Guide Vane, Second Vane Cascade, 1/4 Tip Section   | 29       |
| 28         | Redesigned Inlet Guide Vane, Second Vane Cascade, 3/8 Tip Section   | 29       |
| 29         | Redesigned Inlet Guide Vane, Second Vane Cascade, Tip Section   | 30       |
| 30         | Pressure Loss Contours, Second Vane-Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes  | 31       |
| 31         | Exit Gas Angle Contours, Second Vane-Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.912, Baseline with Redesigned Inlet Guide Vanes | 32       |
| 32         | Spanwise Pressure Loss Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes          | 33       |
| 33         | Spanwise Loss Coefficient Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. = 0.912 Baseline With Redesigned Inlet Guide Vanes        | 34       |
| 34         | Spanwise Exit Gas Angle Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. = 0.912, Baseline with Redesigned Inlet Guide Vanes         | 35       |
| 35         | Spanwise Exit Mach Number Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. = 0.912, Baseline With Redesign Inlet Guide Vanes         | 36       |
| 36         | Inlet Duct Loss Versus Percent Radial Span -Second Vane Baseline With Redesigned Inlet Guide Vanes  | 37       |
| 37         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes-Root Section                   | 37       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 38         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes—Mean Section  | 38       |
| 39         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord Second Vane Baseline with Redesigned Inlet Guide Vanes Tip Section  | 38       |
| 40         | Pressure Loss Contours, Second Vane -Screen Removed, Three Flow Passages, Midspan Exit Mach No. =0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds   | 40       |
| 41         | Exit Gas Angle Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. =0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds | 41       |
| 42         | Spanwise Pressure Loss Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. =0.869, Baseline With Redesign Inlet Guide Vanes and Boundary Layer Bleeds              | 42       |
| 43         | Spanwise Loss Coefficient Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. =0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds       | 43       |
| 44         | Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. =0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds         | 44       |
| 45         | Spanwise Exit Mach Number Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. =0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds       | 45       |
| 46         | Inlet Duct Loss Versus Percent Radial Span -Second Vane Cascade With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds  | 46       |
| 47         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds—Root Section                    | 46       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 47         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds-Root Section                              | 46       |
| 48         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds - Mean Section                            | 47       |
| 49         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds - Tip Section                             | 47       |
| 50         | Oil and Graphite Flow Patterns - Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Upstream Inside Diameter; Midspan Exit Mach No. = 0.87   | 48       |
| 51         | Oil and Graphite Flow Patterns - Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Outside Diameter; Midspan Exit Mach No.=0.87  | 48       |
| 52         | Oil and Graphite Flow Patterns - Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Inside Diameter; Midspan Exit Mach No. =0.87  | 49       |
| 53         | Oil and Graphite Flow Patterns - Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Outside Diameter; Midspan Exit Mach No. =0.87 | 49       |
| 54         | Oil and Graphite Flow Patterns - Inlet Guide Vane with Original Boundary Layer Bleed Slots; Midspan Exit Mach No. =0.87  | 50       |
| 55         | Pressure Loss Contours, Second Vane-Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.895, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds     | 51       |
| 56         | Exit Gas Angle Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.895, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds  | 52       |
| 57         | Spanwise Pressure Loss Distribution, Screen Removed, Midspan Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                         | 53       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 58         | Spanwise Loss Coefficient Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. =0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                        | 54       |
| 59         | Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. =0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                        | 55       |
| 60         | Spanwise Exit Mach Number Distribution, Second Vane-Screen Removed, Midspan Exit Mach No. =0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                        | 56       |
| 61         | Inlet Duct Loss Versus Percent Radial Span-Second Vane Cascade With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds  | 57       |
| 62         | Pressure Loss Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                | 58       |
| 63         | Exit Gas Angle Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                | 59       |
| 64         | Spanwise Pressure Loss Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                         | 60       |
| 65         | Spanwise Loss Coefficient Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                   | 61       |
| 66         | Spanwise Exit Gas Angle Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                       | 62       |
| 67         | Spanwise Exit Mach Number Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                      | 63       |
| 68         | Oil and Graphite Flow Patterns - Second Vane with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; View of Downstream Inside Diameter; Midspan Exit Mach No. = 0.862 | 64       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 69         | Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; View of Downstream Outside Diameter; Midspan Exit Mach No. =0.862 | 64       |
| 70         | Pressure Loss Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds               | 65       |
| 71         | Exit Gas Angle Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds              | 66       |
| 72         | Spanwise Pressure Loss Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                      | 67       |
| 73         | Spanwise Loss Coefficient Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                    | 68       |
| 74         | Spanwise Exit Gas Angle Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                      | 69       |
| 75         | Spanwise Exit Mach Number Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds                    | 70       |
| 76         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Root Section                   | 71       |
| 77         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Mean Section                   | 71       |
| 78         | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section                    | 72       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 79         | Oil and Graphite Flow Patterns--Second Vane Baseline with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; Midspan Exit Mach No. = 0.860                           | 72       |
| 80         | Oil and Graphite Flow Patterns--Second Vane Baseline with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; Midspan Exit Mach No =0.860                             | 73       |
| 81         | Second Vane Baseline Airfoil Recontouring, Root Section Static Pressure Redistribution  | 75       |
| 82         | Second Vane Baseline Airfoil Recontouring, Tip Section Static Pressure Redistribution   | 76       |
| 83         | Elevation and Section Location of the Recambered and Recontoured Second Vane Airfoils   | 77       |
| 84         | Recontoured Second Vane, Root Section (FF)  | 78       |
| 85         | Recontoured Second Vane, Root Fillet Section (AA)   | 78       |
| 86         | Recontoured Second Vane, 1/4 Root Section (BB)  | 79       |
| 87         | Recontoured Second Vane, Mean Section (CC)  | 79       |
| 88         | Recontoured Second Vane, 1/4 Tip Section (DD)   | 80       |
| 89         | Recontoured Second Vane, Fillet Section (EE)  | 80       |
| 90         | Recontoured Second Vane, Tip Section (HH)   | 81       |
| 91         | Recontoured Second Vane, Tip Defining Section (GG)  | 81       |
| 92         | Pressure Loss Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.863, Recontoured Airfoil; With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds   | 82       |
| 93         | Exit Gas Angle Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes, and Optimum Boundary Layer Bleeds | 83       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 94         | Spanwise Pressure Loss Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds     | 84       |
| 95         | Spanwise Loss Coefficient Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds  | 85       |
| 96         | Spanwise Exit Gas Angle Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds    | 86       |
| 97         | Spanwise Exit Mach Number Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds  | 87       |
| 98         | Comparison of Recontoured Airfoil Spanwise Loss Coefficient Distribution with Baseline Values   | 88       |
| 99         | Oil and Graphite Flow Patterns—Second Vane Recontoured Airfoils; Midspan Exit Mach No. = 0.863  | 89       |
| 100        | Oil and Graphite Flow Patterns—Second Vane Recontoured Airfoils; Midspan Exit Mach No. =0.863   | 89       |
| 101        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen—Root Section       | 90       |
| 102        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Mean Section | 90       |
| 103        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section  | 91       |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 104        | Profile for End Wall Contouring, Inside Diameter Wall  | 93       |
| 105        | Profile for End Wall Contouring, Outside Diameter Wall   | 94       |
| 106        | Pressure Loss Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds  | 95       |
| 107        | Exit Gas Angle Contours, Second Vane-Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds | 96       |
| 108        | Spanwise Pressure Loss Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds          | 97       |
| 109        | Spanwise Loss Coefficient Distribution, Second Vane-Screen Installed, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds       | 98       |
| 110        | Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds       | 99       |
| 111        | Spanwise Exit Mach Number Distribution, Second Vane -Screen Installed, Midspan Exit Mach No. =0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds      | 100      |
| 112        | Comparison of Recontoured End Wall Spanwise Coefficient Distribution with Baseline Values  | 112      |
| 113        | Oil and Graphite Flow Patterns—Second Vane with End Wall Contouring; Midspan Exit Mach No. =0.843  | 101      |
| 114        | Oil and Graphite Flow Patterns—Second Vane with End Wall Contouring; Midspan Exit Mach No. =0.843  | 102      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 115        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen - Root Section   | 102      |
| 116        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen - Mean Section   | 103      |
| 117        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen - Tip Section    | 103      |
| 118        | Second Vane Root Section Recambering   | 105      |
| 119        | Second Vane Tip Section Recambering  | 106      |
| 120        | Recambered Second Vane, Root Section (FF)  | 107      |
| 121        | Recambered Second Vane, Root Fillet Section (AA)   | 107      |
| 122        | Recambered Second Vane, $\frac{1}{4}$ Root Section (BB)  | 108      |
| 123        | Recambered Second Vane, Mean Section (CC)  | 108      |
| 124        | Recambered Second Vane, $\frac{1}{4}$ Tip Section (DD)   | 109      |
| 125        | Recambered Second Vane, Fillet Section (EE)  | 109      |
| 126        | Recambered Second Vane, Tip Section (HH)   | 110      |
| 127        | Recambered Second Vane, Tip Defining Section (GG)  | 110      |
| 128        | Pressure Loss Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds | 111      |
| 129        | Exit Gas Angle Contours, Second Vane -Screen Installed, Three Flow Passages, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds | 112      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 130        | Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds    | 113      |
| 131        | Spanwise Loss Coefficient, Second Vane - Screen Installed, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds              | 114      |
| 132        | Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds   | 115      |
| 133        | Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. =0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds | 116      |
| 134        | Comparison of Recambered Airfoil Spanwise Loss Coefficient Distribution with Baseline Values  | 117      |
| 135        | Oil and Graphite Flow Patterns—Second Vane Recambered Airfoils; Midspan Exit Mach No. =0.880  | 117      |
| 136        | Oil and Graphite Flow Patterns—Second Vane Recambered Airfoils; Midspan Exit Mach No. =0.880  | 118      |
| 137        | Static-to Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Root Section  | 118      |
| 138        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vane, Optimum Boundary Layer Bleeds and Inlet Screen — Mean Section | 119      |
| 139        | Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen — Tip Section | 119      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 140        | Comparison of Baseline Loss Coefficients With Those Of Various Boundary Layer Control Methods  | 120      |
| 141        | Comparison of Baseline Exit Flow Angles With Those of Various Boundary Layer Control Methods   | 121      |
| 142        | Medium Solidity Annular Segment Cascade – Flowpath Cross-Section   | 124      |
| 143        | Typical Installation of Airfoil Surface Static Instrumentation   | 129      |
| 144        | Medium Solidity Annular Segment Cascade—Unfolded View of Test Section  | 129      |
| 145        | Probes Used in Medium Solidity Annular Cascade—From Left to Right: 1.5 Inch Minimum Blockage “Cobra” Probe ( $P_{TOTAL} + A/A$ ), “Knee” Probe (Pitch Angle), “Banjo” Probe ( $P_{STATIC} + A/A$ ) | 130      |
| 146        | Medium Solidity Cascade Probe Calibration  | 131      |
| 147        | Medium Solidity Second Blade Pitch Angle   | 132      |
| 148        | Inlet Guide Vane Pressure Loss Contours, First Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.835  | 134      |
| 149        | Inlet Guide Vane Pressure Loss Contours, First Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.775   | 135      |
| 150        | Inlet Guide Vane Pressure Loss Contours, Second Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.860   | 136      |
| 151        | Inlet Guide Vane Pressure Loss Contours, Second Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.918  | 137      |
| 152        | Inlet Guide Vane Spanwise Pressure Loss Distribution, First Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.775   | 138      |
| 154        | Inlet Guide Vane Spanwise Pressure Loss Distribution, Second Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.860  | 139      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title  | Page No. |
|------------|--|----------|
| 155        | Inlet Guide Vane Spanwise Pressure Loss Distribution, Second Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.918 | 139      |
| 156        | Inlet Guide Vane Spanwise Exit Angle Distribution, First Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.835      | 140      |
| 157        | Inlet Guide Vane Spanwise Exit Angle Distribution, First Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.775     | 141      |
| 158        | Inlet Guide Vane Spanwise Exit Angle Distribution, Second Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.860     | 142      |
| 159        | Inlet Guide Vane Spanwise Exit Angle Distribution, Second Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. =0.918    | 143      |
| 160        | Pressure Loss Contours, First Vane, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. =0.835                               | 144      |
| 161        | Pressure Loss Contours, First Blade, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. =0.775                              | 145      |
| 162        | Exit Gas Angle Contours, First Vane, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. =0.835                              |          |
| 163        | Exit Gas Angle Contours, First Blade, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. =0.775                             | 147      |
| 164        | Spanwise Pressure Loss Distribution, First Vane, Medium Solidity, Midspan Exit Mach No. =0.835                                       |          |
| 165        | Spanwise Pressure Loss Distribution, First Blade, Medium Solidity, Midspan Exit Mach No. =0.775                                      | 149      |
| 166        | Spanwise Loss Coefficient Distribution, First Vane, Medium Solidity, Midspan Exit Mach No. =0.835                                    | 150      |

# UNCLASSIFIED

## LIST OF ILLUSTRATIONS (Cont'd)

| Figure No. | Title   | Page No. |
|------------|---|----------|
| 167        | Spanwise Loss Coefficient Distribution, First Blade, Medium Solidity, Midspan Exit Mach No. =0.775      | 151      |
| 168        | Spanwise Exit Gas Angle Distribution, First Vane, Medium Solidity, Midspan Exit Mach No. =0.835         | 152      |
| 169        | Spanwise Exit Gas Angle Distribution, First Blade, Medium Solidity, Midspan Exit Mach No. =0.775        | 153      |
| 170        | Spanwise Exit Mach Number Distribution, First Vane, Medium Solidity, Midspan Exit Mach No. =0.835       | 154      |
| 171        | Spanwise Exit Mach Number Distribution, First Blade, Medium Solidity, Midspan Exit Mach No. =0.775      | 155      |
| 172        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity--Root Section  | 157      |
| 173        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity--Mean Section  | 157      |
| 174        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity--Tip Section   | 158      |
| 175        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity--Root Section | 159      |
| 176        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity--Mean Section | 159      |
| 177        | Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity--Tip Section  | 160      |

# UNCLASSIFIED

## LIST OF TABLES

| Table No. | Title   | Page No. |
|-----------|---|----------|
| I         | Turbine Design Parameters   | 3        |
| II        | Measured Loss vs Predicted - Baseline Airfoils                    | 4        |
| III       | Effect of Flow Fences and Surface Roughness on Second Vane Losses | 20       |
| IV        | Redesigned Second Vane Cascade Turning Vane                       | 165      |
| V         | Redesigned Second Vane Cascade Turning Vane                       | 166      |
| VI        | Redesigned Second Vane Cascade Turning Vane                       | 167      |
| VII       | Redesigned Second Vane Cascade Turning Vane                       | 168      |
| VIII      | Redesigned Second Vane Cascade Turning Vane                       | 169      |
| IX        | Redesigned Second Vane Cascade Turning Vane                       | 170      |
| X         | Redesigned Second Vane Cascade Turning Vane                       | 171      |
| XI        | Redesigned Second Vane Cascade Turning Vane                       | 172      |
| XII       | Redesigned Second Vane Cascade Turning Vane                       | 173      |
| XIII      | Recontoured Second Vane   | 174      |
| XIV       | Recontoured Second Vane   | 175      |
| XV        | Recontoured Second Vane   | 176      |
| XVI       | Recontoured Second Vane   | 177      |
| XVII      | Recontoured Second Vane   | 178      |
| XVIII     | Recontoured Second Vane   | 179      |
| XIX       | Recontoured Second Vane   | 180      |
| XX        | Recontoured Second Vane   | 181      |
| XXI       | Integrated Average Profile Loss Coefficients Second Vane Cascade  | 122      |

# UNCLASSIFIED

## LIST OF TABLES (Cont'd)

| Table No. | Title   | Page No. |
|-----------|---|----------|
| XXII      | Airfoil Static Pressure Instrumentation Medium Solidity                           | 125      |
| XXIII     | Airfoil Static Pressure Instrumentation Medium Solidity<br>First Stage Blade      | 126      |
| XXIV      | Airfoil Static Pressure Instrumentation Medium Solidity<br>Second Stage Vane      | 127      |
| XXV       | Airfoil Static Pressure Instrumentation Medium Solidity<br>Second Stage Blade     | 128      |
| XXVI      | Medium Solidity First Vane Profile Loss Coefficient Variations<br>at Mean Section | 156      |

# UNCLASSIFIED

## LIST OF SYMBOLS

|             |   |
|-------------|---|
| A           | - area, square inches   |
| B           | - axial chord, inches   |
| C           | - absolute gas velocity, feet per second                      |
| $C_F$       | - drag coefficient  |
| $C_L$       | - Zweifel load coefficient                                    |
| $C_L^*$     | - load coefficient, $\Delta C_u/U$                            |
| E           | - diffusion parameter   |
| H           | - boundary layer shape factor                                 |
| $\Delta H$  | - work, Btu per pound   |
| M           | - Mach number   |
| P           | - pressure, psia  |
| $\Delta P$  | - pressure rise from minimum to exit value on suction surface |
| Q           | - exit dynamic head   |
| R           | - fillet radius, inches                                       |
| $R_C$       | - radius of curvature, inches                                 |
| $Re_\theta$ | - Reynolds number based on boundary layer momentum thickness  |
| S           | - distance along airfoil surface, inches                      |
| T           | - temperature, °R   |
| u           | - tangential velocity, feet per second                        |
| W           | - relative gas velocity, feet per second                      |
| $W_g$       | - gas flow, pounds per second                                 |
| X           | - axial distance, inches                                      |
| Y           | - tangential distance, inches                                 |
| Z           | - number of airfoils  |
| $\alpha$    | - absolute gas angle, degrees                                 |
| $\beta$     | - relative gas angle degrees                                  |
| $\delta$    | - boundary layer thickness, inches                            |
| $\delta^*$  | - boundary layer displacement thickness                       |
| $\theta$    | - boundary layer momentum thickness, inches                   |
| $\theta_b$  | - blade camber, degrees                                       |
| $\theta_v$  | - vane camber, degrees  |
| $\tau$      | - gap, inches   |
| $\eta$      | - efficiency, percent   |

### Subscripts

|   |                                    |
|---|------------------------------------|
| 0 | inlet to first vane                |
| 1 | inlet to first blade               |
| 2 | exit from stage or airfoil section |

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## LIST OF SYMBOLS (Cont'd)

|    |                    |
|----|--------------------|
| G  | gage point         |
| ws | wetted surface     |
| ms | mainstream surface |
| S  | static             |
| T  | total              |

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PAGE NO. XXV

# UNCLASSIFIED

UNCLASSIFIED

PAGE NO. xxvi

UNCLASSIFIED

SECTION I  
INTRODUCTION

# UNCLASSIFIED

## SECTION I

### INTRODUCTION

(U) Design analysis and optimization studies of aircraft jet engines involve a trade between component efficiencies and engine size and weight. Advanced mission studies show that the bypass turbofan engine, which has seen increased use in recent military aircraft applications, will continue to be of primary interest. One characteristic of the turbofan is that fuel economy increases with bypass ratio. Higher bypass ratios require increased fan power to be supplied by the fan drive or low-pressure turbine. However, the increased turbine power requirements must be met without a turbine efficiency decrement.

(U) The efficiency of a turbine is determined by the turbine diameter, rotational speed, number of stages and airfoil loading. In particular, fan-drive turbine design is constrained by several other requirements. The rotational speed of the turbine must be limited in order that the fan tip Mach number does not exceed the limit for acceptable losses. For higher bypass ratios, where larger fan diameters are required, this problem is further aggravated. Applying conventional aerodynamics, at fixed rotational speed, increased work can only be realized by a further increase in the number of stages and/or the turbine diameter. Reduction of the turbine diameter or airfoil solidity results in a lighter turbine, but also leads to a sacrifice in efficiency due to losses associated with increased airfoil loading. If the turbine diameter and solidity can be reduced without a penalty in turbine efficiency, considerable gains can be realized by the engine. Therefore, the promise of turbofan engines depends to a large extent on improved fan-drive turbine technology.

(U) The objective of the work done under this contract is to analyze and test concepts which will increase the fan-drive turbine loading while maintaining or increasing the efficiency level. The goals of this program are to develop design procedures and turbine aerodynamic techniques for efficient high-work, low-pressure turbines by means of analytical studies and cascade testing, and to demonstrate the effectiveness of the techniques by designing and testing a two-stage turbine that meets or exceeds the Contract stage-work and efficiency goals.

(U) The complete program is being conducted in four phases over a three year period which commenced on 1 January 1968. Phase I defined the basic turbine design and an analysis of promising increased loading concepts was completed. The results of the Phase I study were reported in the Reference 1 Report. Phases II and III consist of experimental testing to verify and extend the turbine aerodynamic techniques and design procedures for high loading levels. The design details of the baseline cascade test airfoils for both the annular segment and plane cascade rig were reported in the Reference 2 Report. The results of the annular cascade testing of the four baseline airfoils were reported in the Reference 3 Report. Phase IV will subject the aerodynamic techniques and design procedure to a two-stage rotating rig test.

(U) Work on the Contract during this report period proceeded on Phase II and the design and fabrication effort of Phase III. Design work was initiated on Phase IV. The results of the boundary layer control technique evaluations and the medium solidity baseline tests are described in this Report. The status of the remaining Phase II tasks is also presented.

PAGE NO. 1

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# UNCLASSIFIED

UNCLASSIFIED

PAGE NO. 2

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**SECTION II  
BACKGROUND**

SECTION II

BACKGROUND

(U) The objective of Phase I study was to select a preliminary turbine design that is capable of meeting the performance requirements of this Contract. These requirements are summarized in Table I.

TABLE I  
TURBINE DESIGN PARAMETERS

|   |  |
|---|--|
| Number of Stages                          | 2  |
| Average Load Coefficient, $C_L^*$         | 2.2  |
| First Blade Tip Wheel Speed               | 1000 fps                                   |
| First Blade Inlet Hub-Tip Diameter Ratio  | $\leq 0.8$                                 |
| Exit Swirl Angle-Without Exit Guide Vanes | $20^\circ$                                 |
| Exit Swirl Angle-With Exit Guide Vanes    | $0^\circ$                                  |
| Turbine Inlet Temperature                 | $1450^\circ\text{F}$                       |
| Airflow                                   | $\geq 50$ lbs/sec                          |
| Average Stage Efficiency                  | 91%  |
| Life                                      | <del>                    </del> 10,000 hrs |

(U) The Phase I analysis has been completed and the results were reported in the Reference 1 Report. These analyses included the consideration of flowpath, reaction level, load coefficient level, and variations in work distribution for which velocity triangles were generated. Furthermore, as part of Phase I, preliminary airfoil contours were defined for the same velocity triangles at three levels of reaction and three levels of solidity for the resulting stages.

(U) The medium-reaction, normal solidity airfoils were selected for the Phase II and III baseline evaluations. These airfoil sections were then subjected to additional refinement, which included evaluation of the two-dimensional boundary layer behavior. The baseline airfoil contours, for the first and second vanes and the first and second blades, were described in the Reference 2 Report. All of the baseline airfoils were fabricated and evaluated in an annular segment cascade. These results were presented in the Reference 3 Report. A summary of the test results is shown in Table II, where the measured loss coefficients ( $1-\phi^2$ ) are tabulated.

TABLE II  
MEASURED LOSS VS PREDICTED - BASELINE AIRFOILS

|              | Turbine Design<br>Midspan Exit<br>Mach. No. | Midspan         |             |                                | Overall         |       |
|--------------|---|-----------------|-------------|--------------------------------|-----------------|-------|
|              |   | Test            | Correlation | Predicted<br>Boundary<br>Layer | Test            | Pred. |
| First Vane   | 0.854                                       | 0.017<br>0.023* | 0.031       | 0.032                          | 0.034<br>0.032* | 0.049 |
| First Blade  | 0.780                                       | 0.0266          | 0.036       | 0.049                          | 0.040           | 0.054 |
| Second Vane  | 0.869                                       | 0.021<br>0.028* | 0.036       | 0.046                          | 0.030<br>0.034* | 0.050 |
| Second Blade | 0.904                                       | 0.028           | 0.030       | 0.044                          | 0.038           | 0.042 |

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\*With inlet turbulence screen

(U) The baseline second vane was chosen for further end wall loss study by the process of elimination. The first-stage vane and blade inside diameter end-wall extensions indicated some separation beyond the test cascade which could influence probe readings near this wall in future tests if it became more severe. The short second stage blade chord makes the fabrication of end-wall boundary layer control techniques difficult.

(U) Four boundary layer control techniques were selected for application to the second vane airfoil. These airfoil variations were fabricated and the results of tests conducted on the four variations are presented in this report.

(U) As part of Phase II, lower solidity airfoils were also designed. These airfoils were designed for a 15 percent increase in Zweifel load coefficient and are referred to as medium solidity airfoils in reports under this Contract. The airfoil section and fabrication coordinates were reported in the Reference 3 Report. These airfoils were fabricated and evaluated during this report period. The results are presented in this report.

**SECTION III**  
**TWO-DIMENSIONAL DESIGN VERIFICATION (TASK IIa)**

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## SECTION III

### TWO-DIMENSIONAL DESIGN VERIFICATION (TASK IIa)

#### 1. RFP OBJECTIVE

(U) Provide an experimental verification of the two-dimensional design characteristics.

#### 2. TASK OBJECTIVE

(U) The purpose of this Task is to conduct plane cascade tests in order to verify the aerodynamic concepts applied to the turbine design during the Phase I Program, and to establish the two-dimensional loss levels for the chosen turbine airfoil profiles at design conditions.

(U) The plane cascade tests will serve two equally important purposes. First, the measured profile losses will be compared with those contained in the existing design procedures in order to verify their accuracy. Secondly, the total pressure and flow angle profiles at the exit plane will indicate whether or not the surface boundary layer has separated. Each airfoil has been designed so that such two-dimensional separation should not occur, and these tests will constitute a verification of the entire airfoil section design procedure.

#### 3. STATUS

(U) Six medium-reaction normal-solidity airfoil section cascades were designed and fabricated. The design details of the airfoil sections, including the airfoil coordinates and fabrication details of the cascade test packs, were presented in the Reference 2 Report.

(U) Three of the cascade packs have been tested and the fourth is currently being evaluated. Data analysis is proceeding on the tested airfoils. However, for completeness, the results of the plane cascade testing will be reported in the next Interim Technical Report, when the results of all six cascade tests will be available.

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SECTION IV  
BOUNDARY LAYER CONTROL EVALUATION (TAKS IIc)

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## SECTION IV

### BOUNDARY LAYER CONTROL EVALUATION (TASK IIc)

#### 1. RFP OBJECTIVE

(U) Determine the effects of the most promising boundary layer control techniques on corner flow separation.

#### 2. TASK OBJECTIVE

(U) The RFP objective indicates that methods to eliminate corner flow separation will be considered. Subsequent baseline tests indicated that the end-wall problem for these airfoils was not corner boundary layer separation, but rather the secondary flow of the end-wall boundary layer across the channel. This can be seen in the baseline tests as high loss regions in all suction surface corners. These regions probably originate on the end-wall, but migrate from pressure surface to suction surface and accumulate in the corners. Therefore, the boundary layer control methods that apply to the baseline airfoils are those that reduce the secondary flow at the end-walls.

(U) Four boundary layer control methods were selected and these were applied to one airfoil. The chosen airfoil was the second vane, for reasons given in Section II. The selected methods that were experimentally evaluated are:

- flow fences and increased surface roughness
- local airfoil recontouring
- end-wall contouring
- local airfoil recambering

The results of these tests will be presented in the above order.

(U) These task objectives were met, and the task was completed by the following steps:

- Application of four methods of boundary layer control techniques indicating the best potential for lowering end loss
- Measurement of all important aerodynamic properties at the cascade inlet and exit planes
- Measurement at design Reynolds Number and design incidence for three exit Mach numbers
- Reconstruction of the entire exit plane loss distribution
- Reconstruction of the entire exit plane flow pattern
- Flow visualization of the airfoil and end-wall flow patterns
- Careful analysis of all data and visual clues
- Measurement of the airfoil surface static pressure distributions at three radial locations
- Evaluation of the effectiveness of each boundary layer control method, relative to each other and to the baseline test results
- Selection of best boundary layer control technique for optimization

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## 3. CASCADE PACK DESIGN

(U) The cascade pack chosen for the boundary layer control technique evaluation was the second vane. The design of the baseline second vane cascade pack was presented in the Reference 2 Report. The boundary layer techniques were applied to this cascade, and the hardware variations for each test will be discussed in the section devoted to each of the boundary layer techniques.

(U) As in the baseline evaluation, airfoil surface static pressure taps were distributed around each cascade test airfoil at the root, mean and tip section. The details of the tap locations were given in the Reference 3 Report.

(U) A single cone probe was used for simultaneously measuring local exit plane total pressure static pressure, and exit gas flow angle. Details of the probe design were presented in the Reference 2 Report. The probe was calibrated to determine total and static pressure errors due to the pitch angle over the test Mach number range. Based on this calibration and the theoretical pitch angle, corrections were provided for the data reduction program.

(U) A total pressure probe was also installed just upstream of the test airfoils in order to measure the losses of the turning vanes. The total pressure loss measured for the inlet turning vanes was used to determine the local inlet total pressure profile upstream of the test airfoils. Turning vane losses are used to define the test airfoil inlet conditions in the data reduction program which calculates the test airfoil performance.

(U) The inlet flow angle approaching the test airfoils was also measured for the cascade. The value of the incidence angle was determined from this measurement.

(U) The experimental accuracy of the loss coefficient ( $1-\phi^2$ ) is estimated to be  $\pm 0.003$ . Values that will be given during the discussion of the data are to three significant digits. The purpose for doing this is for identification only, since sometimes it is easier to identify a particular test by loss level rather than its physical description.

(U) Data for all tests were taken at the airfoil design Mach number and Reynolds Number, as well as at two other Mach number levels where the Reynolds Number was no longer matched. As the airfoil exit Mach number increases, the Reynolds Number also increases. The general tendency is for the loss level to decrease as Mach number and Reynolds Number increase. This is true until Mach numbers approach and exceed sonic values, causing shocks. Then, in this case, the loss level increases with increasing Mach number and Reynolds Number.

(U) During the course of this investigation, a great number of flow visualization photographs using oil and graphite tracers were taken. These photographs have a number of items in common which should be noted, including

- Profile flow patterns which always indicate transition on the trailing portion of the suction side, a condition found in turbines (with possible exception observed during flow fence/increased roughness test)

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- No flow separation observed on the airfoil profile, verifying the validity of the airfoil surface static pressure distribution program
- Attached flow on the cascade end-wall extensions which substantiates use of the second vane for these tests
- Indication of a strong corner or secondary flow effect in the suction surface and end-wall corners, with no sign of separation, implying that the important thing to do is to decrease the cross-flow.

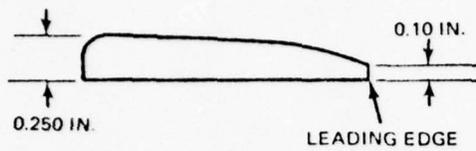
## 4. FLOW FENCE AND INCREASED SURFACE ROUGHNESS

(U) Even though there was considerable doubt about their effectiveness in controlling secondary flows, two methods that were given some consideration were the use of a flow fence and increased surface roughness. The intention of the flow fence was to block or impede channel cross-flows at the end walls, while the intention of the increased surface roughness was to force the boundary layer to be turbulent and, consequently, as thin as possible. These tests were carried out in spite of the lack of promise largely because they were easily added on to the primary test program, and because it was felt that they would add to our understanding of secondary flows. It was also possible to do this testing without interfering with the primary test schedule. Both methods were, in fact, simultaneously tested on opposite walls of the same cascade.

(U) The design of the flow fence was described in the Reference 3 Report, and is shown in Figure 1 for convenience. This fence was applied to the second vane outside diameter wall and its height was obtained from the suction surface secondary flow patterns that were observed in the baseline tests reported in the Reference 3 Report. Those patterns indicated a radially inward movement of the boundary layer at the airfoil trailing edge, extending approximately 0.5 inch from the wall surface. Allowing for the growth of the corner vortex size from inside the passage to the exit plane, the fence height required to significantly reduce the end wall cross-flow was estimated to be one-half the trailing edge size, or 0.5 percent of the span. The fence was mounted in four passages midway between airfoil surfaces and extended the full passage length from leading edge to trailing edge (see Figure 2).

(U) Roughening of the inside diameter wall was accomplished by attaching emery cloth to the end-wall region in four passages. Calculations of the wall boundary layer indicated that the boundary layer would be transitional in the region between the inlet guide vanes and test airfoils. Since this calculation involved approximation of the pressure gradient through the rig, it was decided to increase the surface roughness in case the boundary layer had not transitioned. The calculated boundary layer thickness prior to transition was 0.20 inch. A No. 50 grit emery cloth with a roughness height of 0.013 inch was used. This height is greater than the computed critical value required for boundary layer transition. The emery cloth was cemented to the inside diameter end-wall and to the leading edges of the airfoils adjacent to the inside diameter wall (See Figure 3).

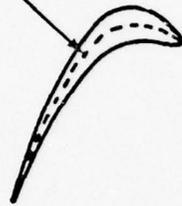
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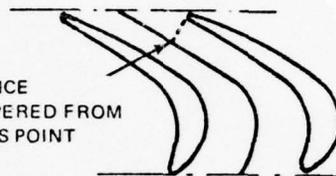
ELEVATION

1. FENCES ARE MADE FROM 0.020 SHIM STOCK
2. FENCES TACKWELDED IN PLACE THEN BRAZED. BRAZE RADIUSED AROUND ROOT TO 0.030 - 0.050 INCHES.
3. FENCES CENTERED BETWEEN AIRFOILS AS SHOWN

SHEET METAL FENCE FORMED TO THIS LINE



FENCE TAPERED FROM THIS POINT



FENCE INSTALLATION

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Figure 1 Second Vane O. D. Shroud Flow Fence Installation



Figure 2 Oil and Graphite Flow Patterns—Second Vane with View of Outside Diameter Flow Fences; Midspan Exit Mach No. =0.903

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Figure 3 Oil and Graphite Flow Patterns—Second Vane with View of Inside Diameter Increased Surface Roughness; Midspan Exit Mach No. =0.903

(U) Plots of the important aerodynamic quantities based on the inlet and exit plane measurements for each test will always be presented in the following order and will be simply referred to as performance data in this Report:

- total pressure loss contour plots
- exit gas angle contour plots
- average spanwise total pressure loss distribution
- average spanwise loss coefficient distribution
- average spanwise exit flow angle distribution
- average spanwise exit Mach number distribution.

The performance data for the flow fence and increased surface roughness test are shown in Figures 4 through 9. Also, a plot of the inlet guide vane and duct loss is shown in Figure 10.

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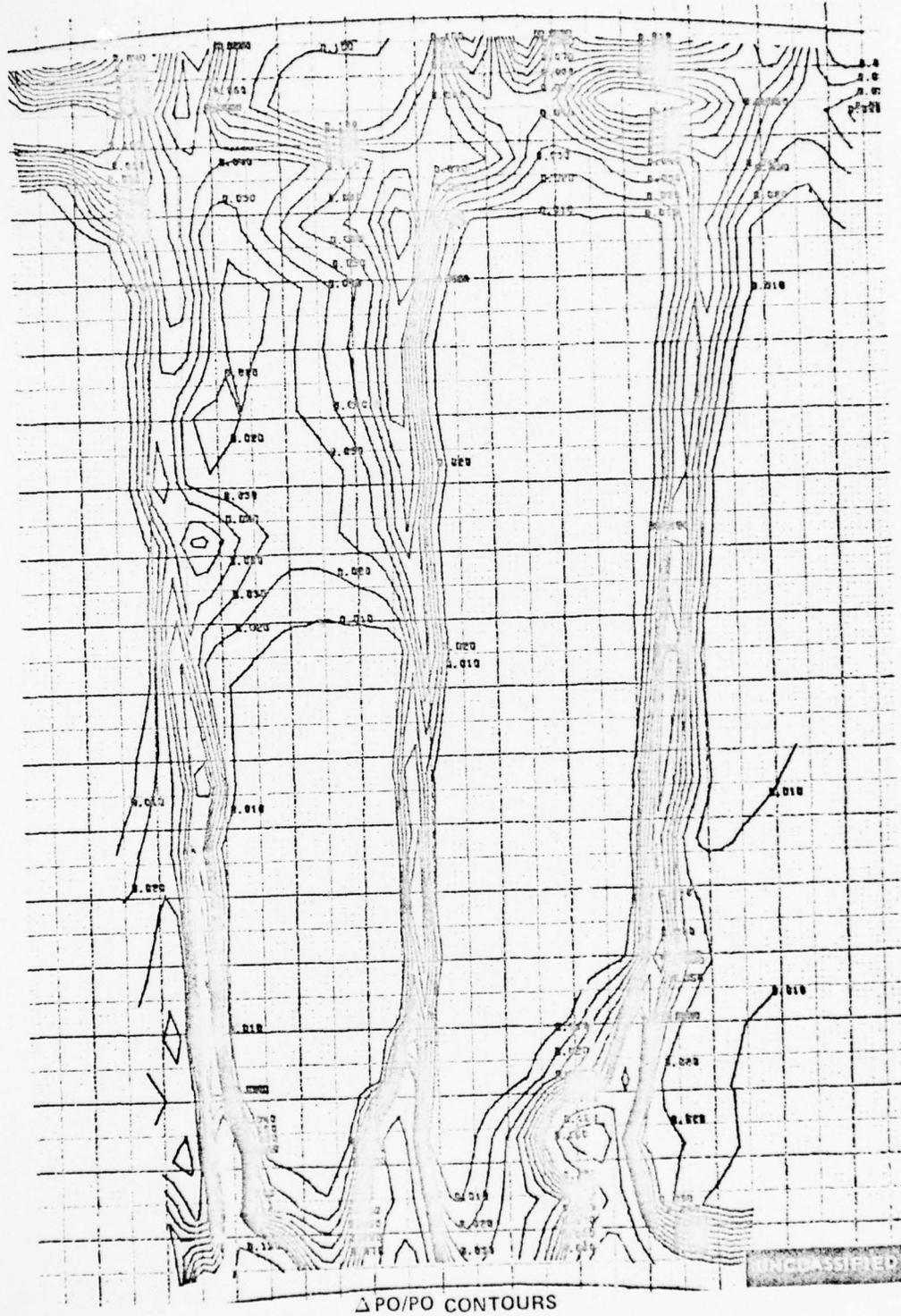


Figure 4 Pressure Loss Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.903, O. D. Flow Fences and I. D. Roughness

PAGE NO. 12

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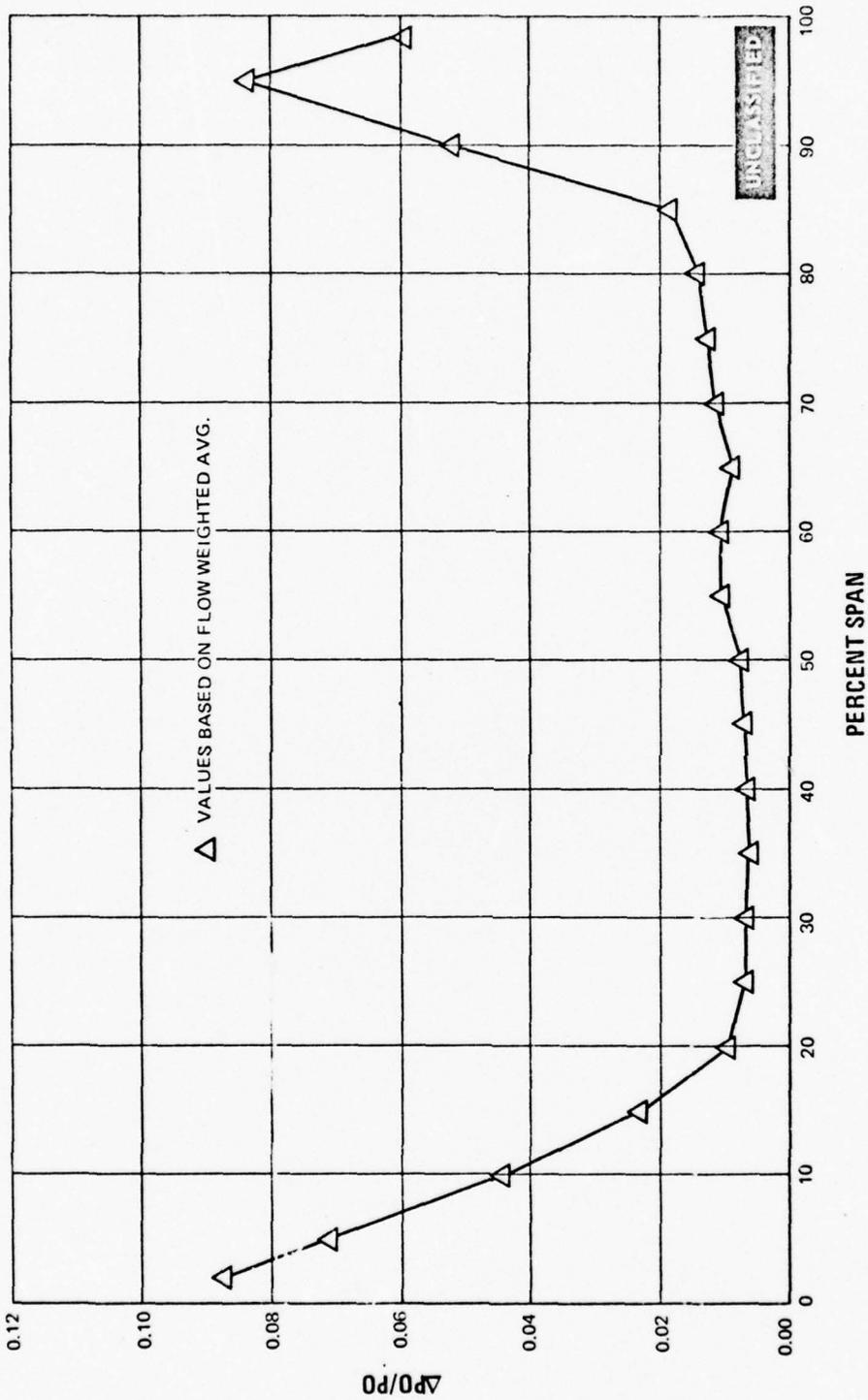


Figure 6 Spanwise Pressure Loss Distribution, Second Vane - Screen Removed, Midspan  
Exit Mach No. = 0.903, O. D. Flow Fences and I. D. Roughness

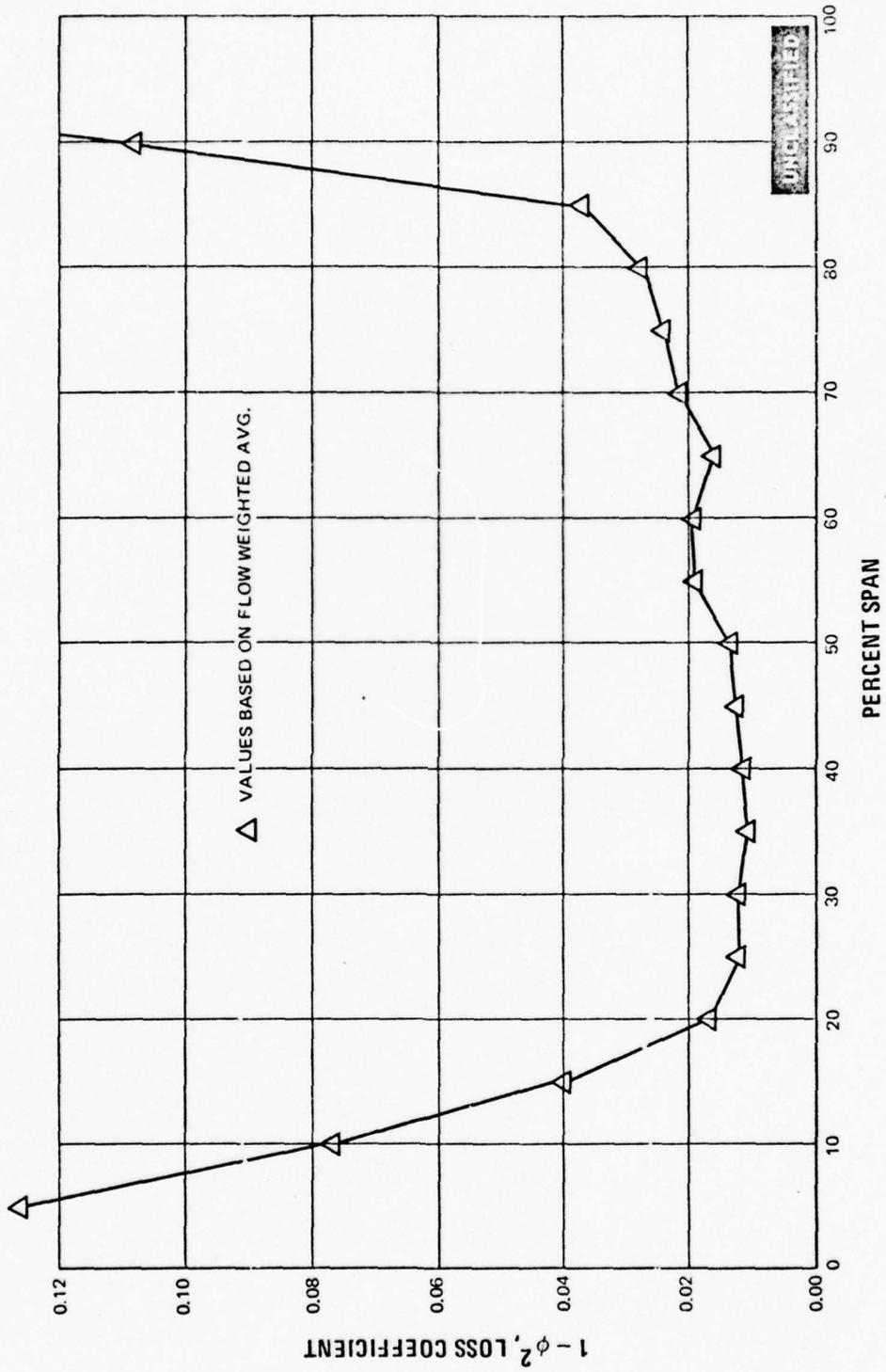


Figure 7 Spanwise Loss Coefficient Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.903, O. D. Flow Fences and I. D. Roughness

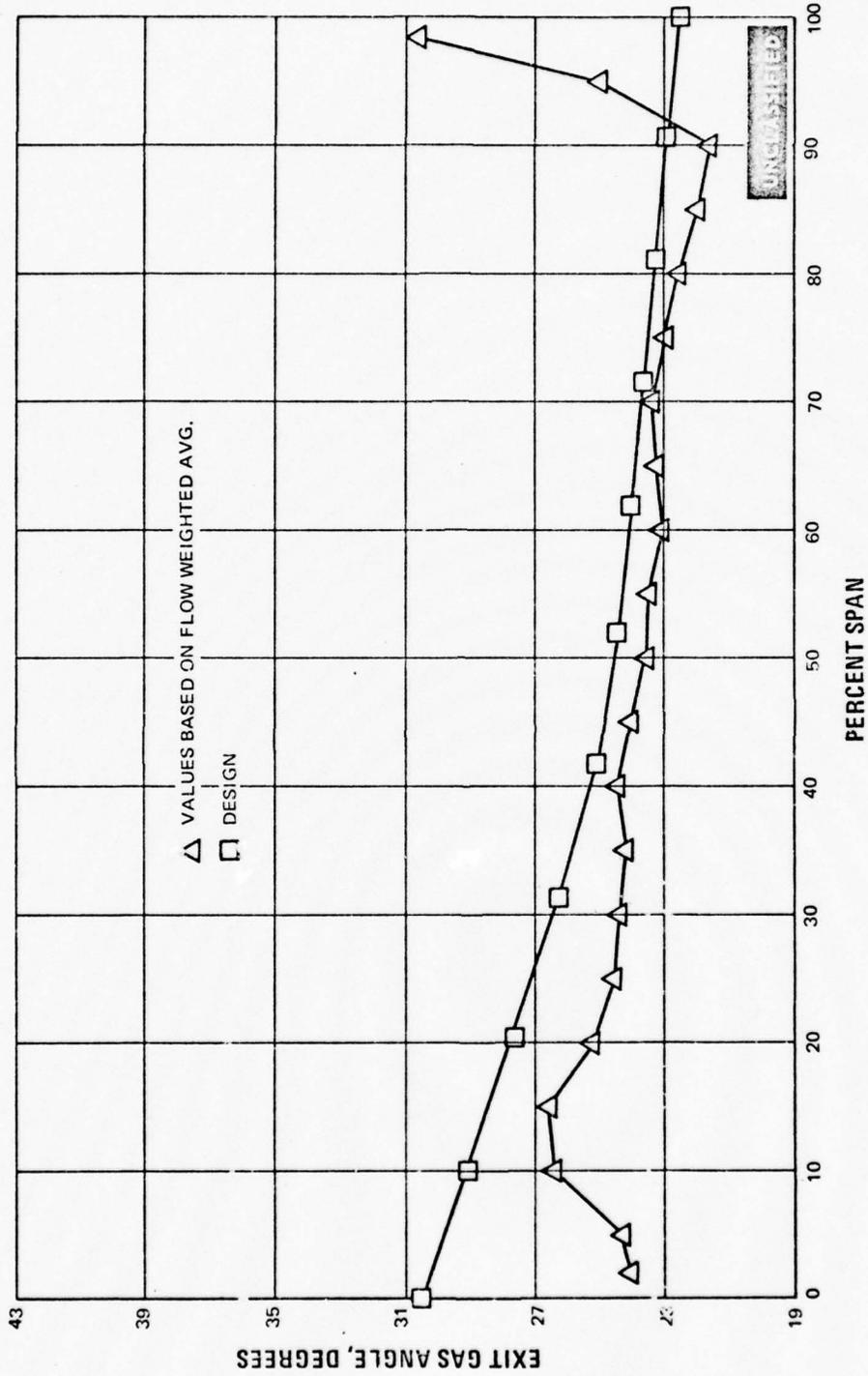


Figure 8 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.903, O. D. Flow Fences and I. D. Roughness

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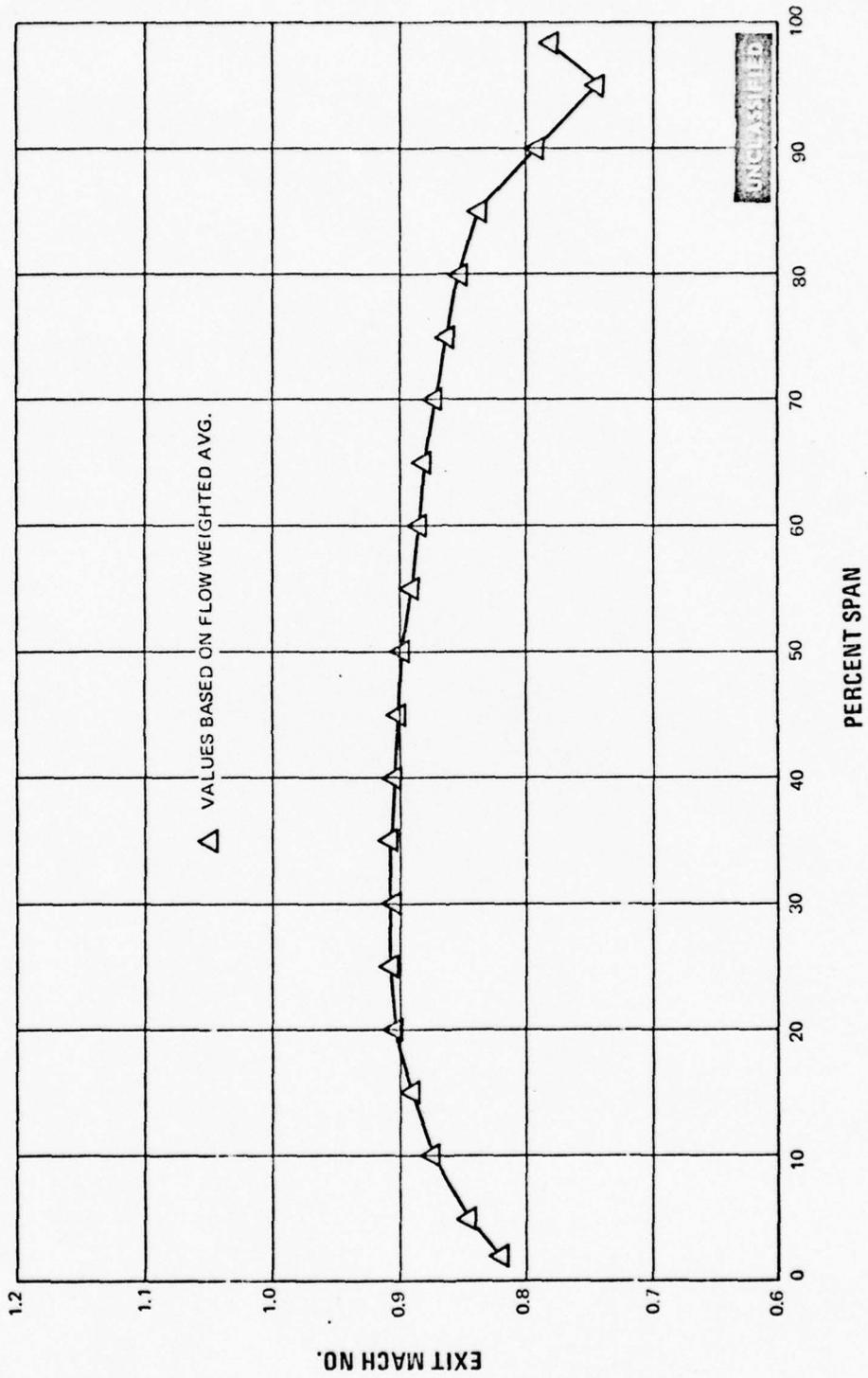


Figure 9 Spanwise Exit Mach Number Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. = 0.903, O. D. Flow Fences and I. D. Roughness

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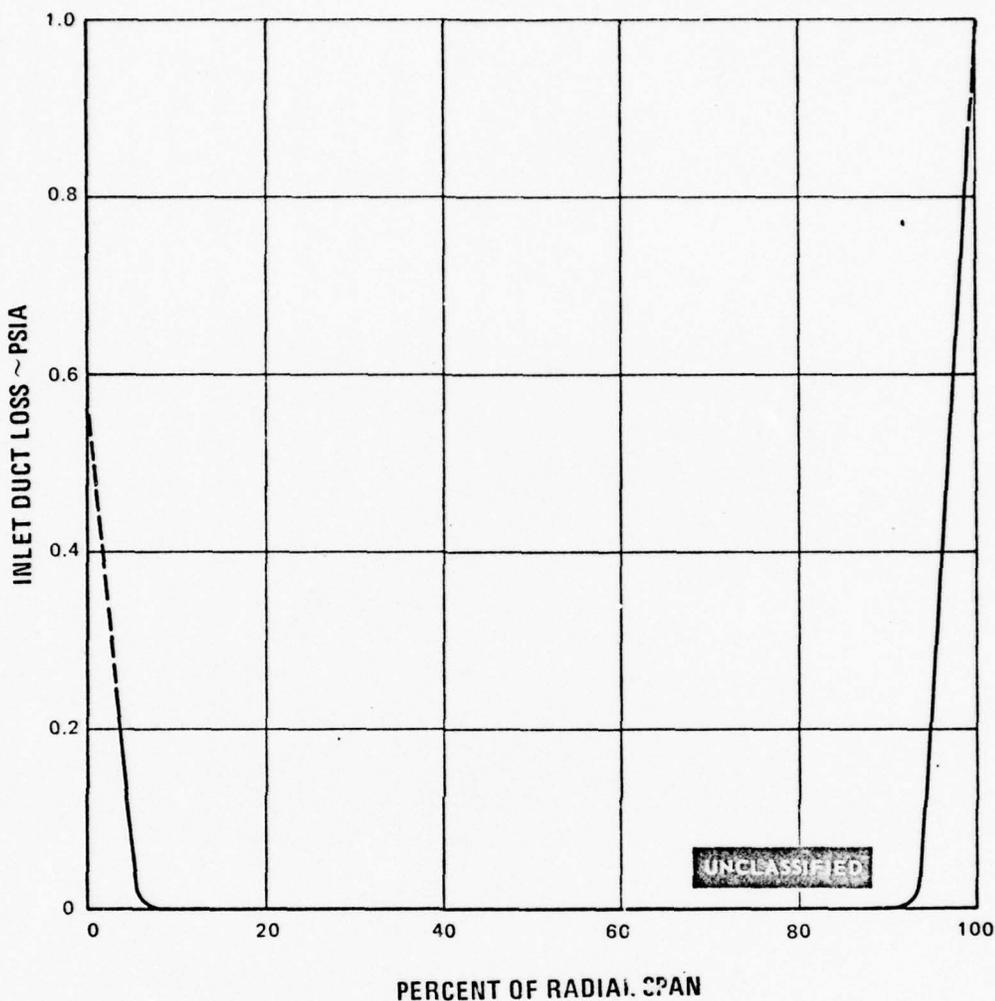


Figure 10 Inlet Duct Loss Versus Percent Radial Span—Second Vane Cascade With I.D. Roughness and O.D. Flow Fences

(U) A comparison plot of the average spanwise loss variation for the flow fence and increased roughness, versus baseline loss coefficients, is shown in Figure 11 at approximately the same Mach number. The variation of the loss coefficient with Mach number can be seen to be very slight from the data of Figure 12. The contribution of each end to the overall loss is shown separately in Figure 13, in order to evaluate the effect of each end-wall treatment. A summary of these results is tabulated in Table III, where the loss values are compared with the baseline test values. Both treatments resulted in increased end-wall losses, although an unexpected improvement was observed in the midspan region. The low midspan values appear inconsistent, but since the end losses were considerably higher than the baseline values, it was not worthwhile to pursue the flow fence and increased surface roughness techniques.

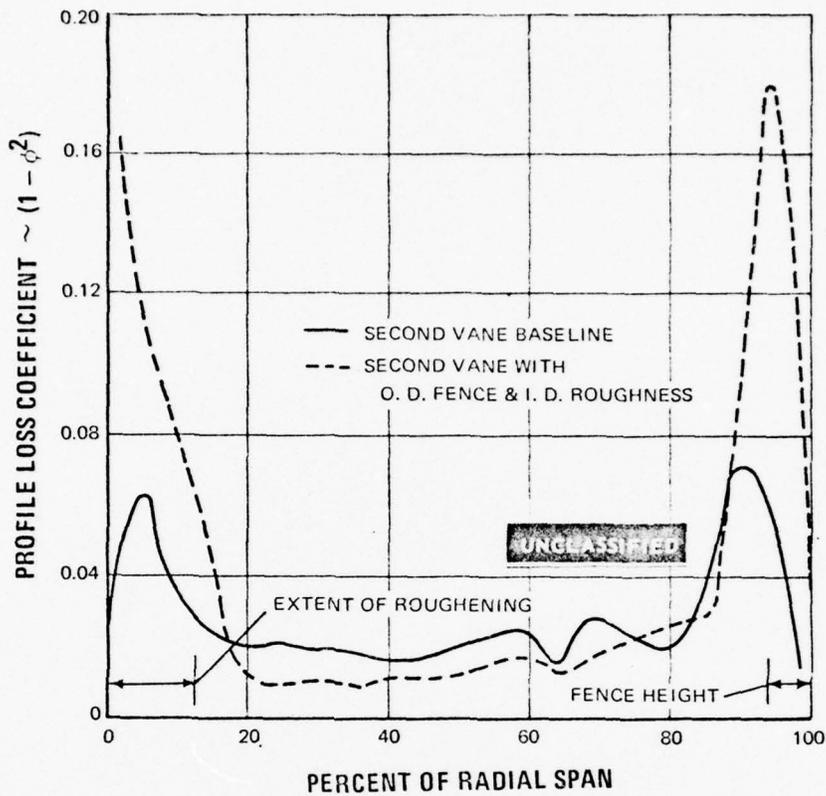


Figure 11 Comparison of O. D. Flow Fence and I. D. Roughness Loss Coefficient Distribution with Baseline Values

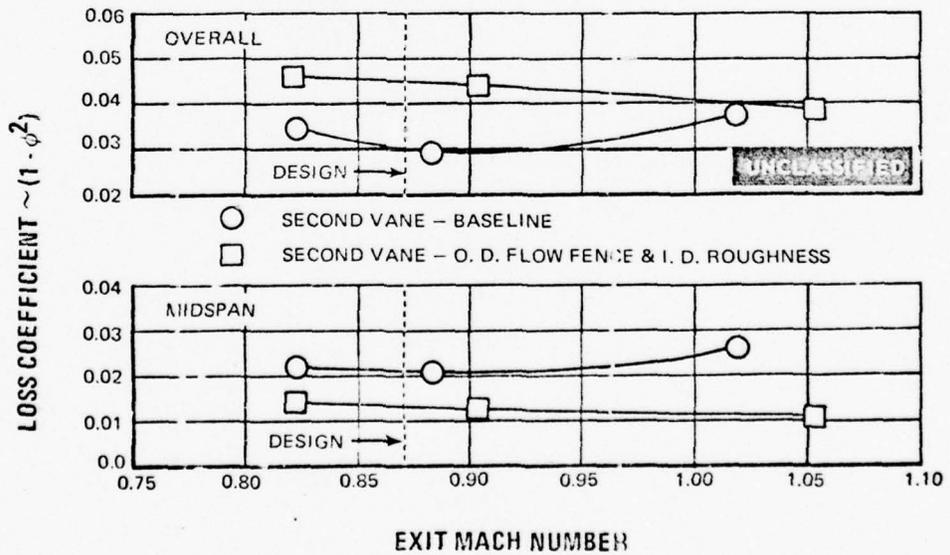


Figure 12 Effect of Mach Number on Profile Loss Coefficient for O. D. Flow Fence and I. D. Increased Roughness Evaluation

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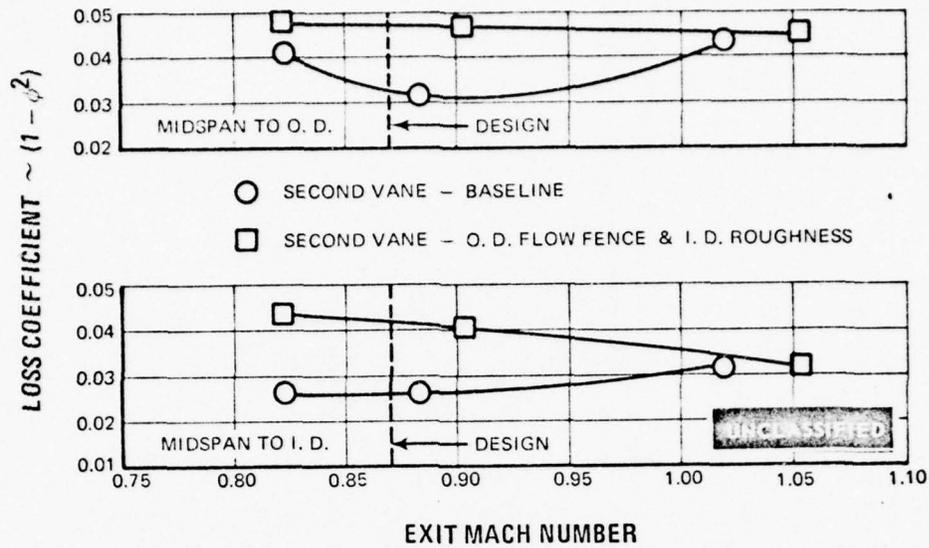


Figure 13 Effect of Mach Number on Profile Loss Coefficient for O. D. Flow Fence and I. D. Increased Roughness Evaluation

TABLE III

EFFECT OF FLOW FENCES AND SURFACE ROUGHNESS ON SECOND VANE LOSSES

Profile Loss Coefficients  $(1-\phi^2)$

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|                               | Midspan | Overall | Midspan to I.D. (Roughness) | Midspan to O. D. (Fences) | Midspan Exit Mach No. |
|-------------------------------|---------|---------|-----------------------------|---------------------------|-----------------------|
| Baseline (Test)               | 0.021   | 0.030   | 0.026                       | 0.033                     | 0.883                 |
| Boundary Layer Control (Test) | 0.013   | 0.045   | 0.042                       | 0.047                     | 0.903                 |
| Baseline (Predicted)          | 0.036   | 0.050   | -                           | -                         | 0.870                 |

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(U) The shift in position of the maximum circumferentially integrated loss from 90 to 94 percent span (See Figure 11) corresponds to a shift in the center of the suction corner vortex from 84 to 94 percent span, indicating the reduced migration effect with reduced secondary flow. However, the peak loss at the vortex center increased from about 7 percent for the baseline to 18 percent by the fences. The inside wall loss indicated a continuous increase toward the wall due to the surface roughening, without the decrease shown in the baseline data. Apparently, the end wall boundary layer had in fact transitioned to turbulent flow and the rougher surface merely increased the frictional drag.

(U) Comparison of the baseline gas exit angle spanwise distribution with the flow fence /increased surface roughness exit gas angles is shown in Figure 14. The discharge angle was not affected by the end-wall treatments except at the outside wall, where the anticipated reduction in overturning due to reduced secondary flow is indicated.

(U) To provide additional clues as to the behavior of the flow in the cascade, a mixture of oil and graphite was painted on the airfoils. Figures 2 and 3, and Figures 15 and 16 show the location of the flow fences on the outside wall and the emery cloth on the inside wall. The patterns indicated that the corner flow remained attached, although the end-wall losses are high.

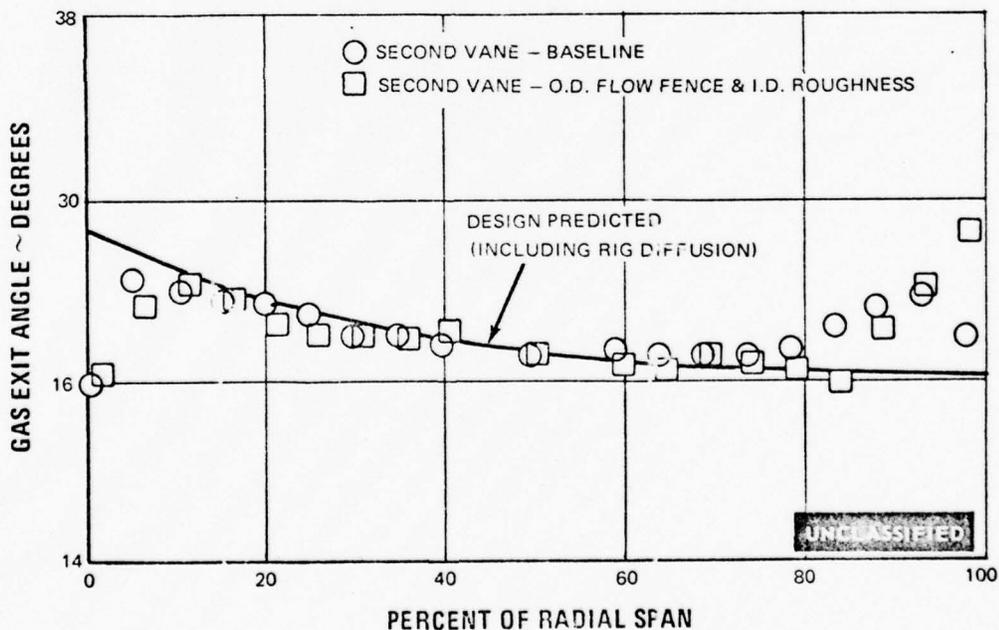


Figure 14 Comparison of Spanwise Averaged Exit Gas Angle Baseline Distribution and Angles Measured with Flow Fences/Surface Roughness.

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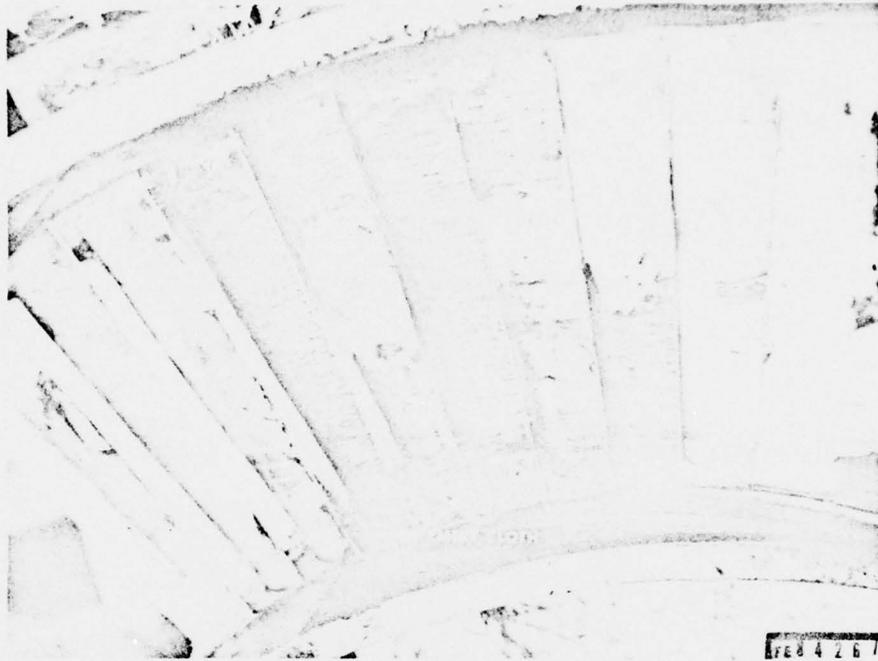


Figure 15 Oil and Graphite Flow Patterns—Second Vane with View of Both Flow Fence and Increased Surface Roughness Effects; Midspan Exit Mach No. =0.903



Figure 16 Oil and Graphite Flow Patterns—Second Vane with View of Both Flow Fence and Increased Surface Roughness Effects; Midspan Exit Mach No. =0.903

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(U) The airfoil surface static pressure distribution at the root, mean and tip are shown in Figures 17 through 19, respectively. The measured loading in the midspan region was almost identical to the desired value. The loading at the root and tip sections does not correspond to the design values, primarily due to the exit-plane effect explained in detail in the Reference 3 Report. This is primarily due to the fundamental difference between the annular segment cascade and rotating rig, since the limited extension of the inside and outside diameter walls tends to make the exit plane static pressure uniform and atmospheric, rather than reproducing the radially increasing static pressure of the axisymmetric rotating flow. Therefore, the airfoil roots are slightly less loaded, and the airfoil tips are slightly more loaded, than the complete turbine required. The situation is further complicated by the fact that the root and tip are both unloaded because they must turn fluid having a lower than average velocity.

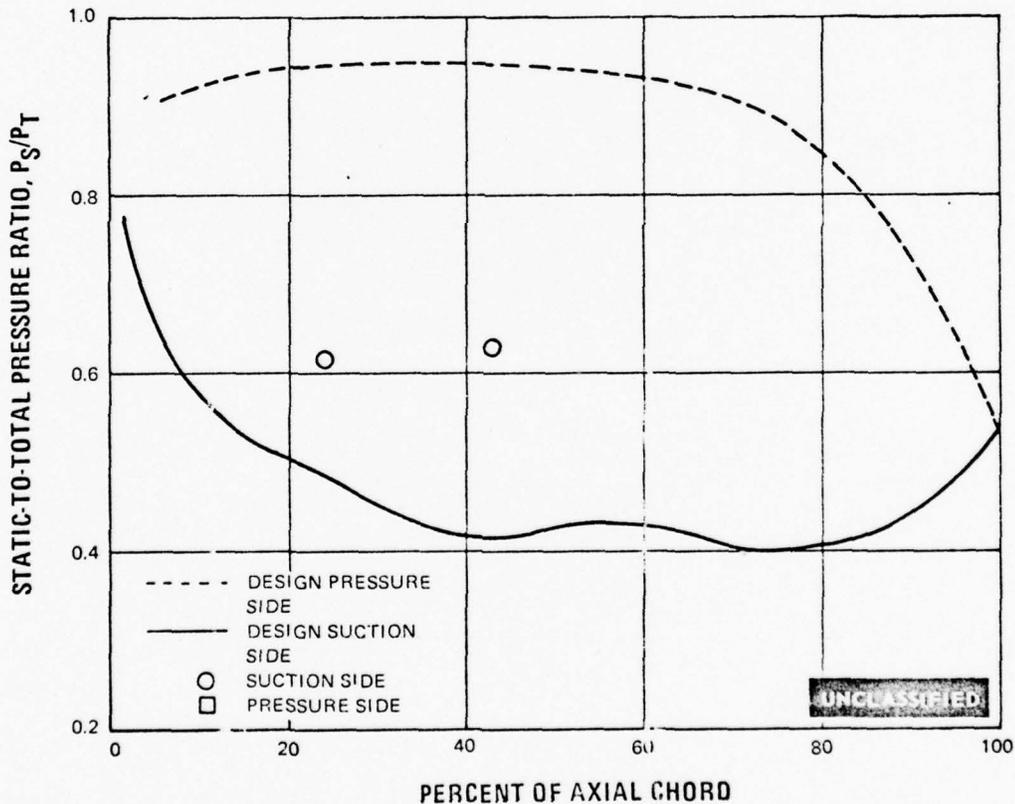


Figure 17 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences—Foot Section

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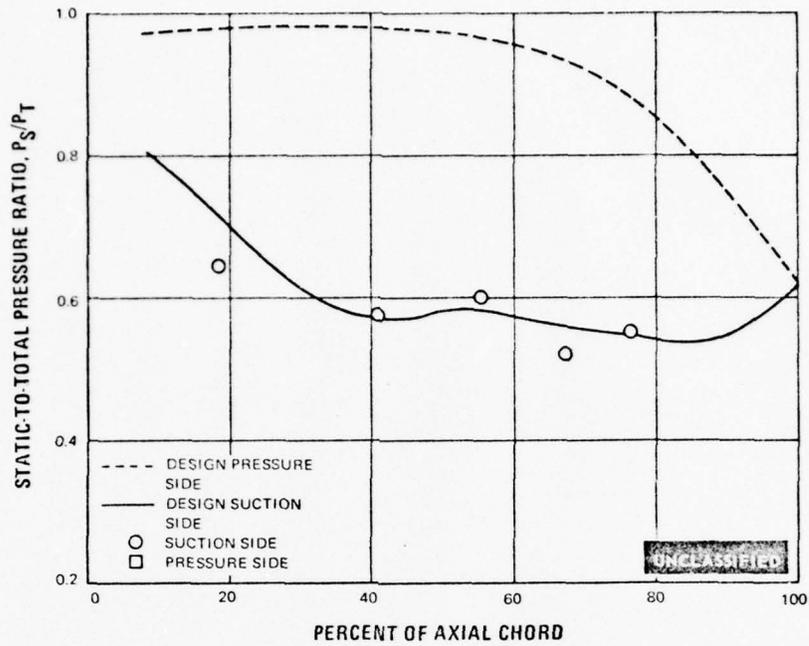


Figure 18 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences - Mean Section

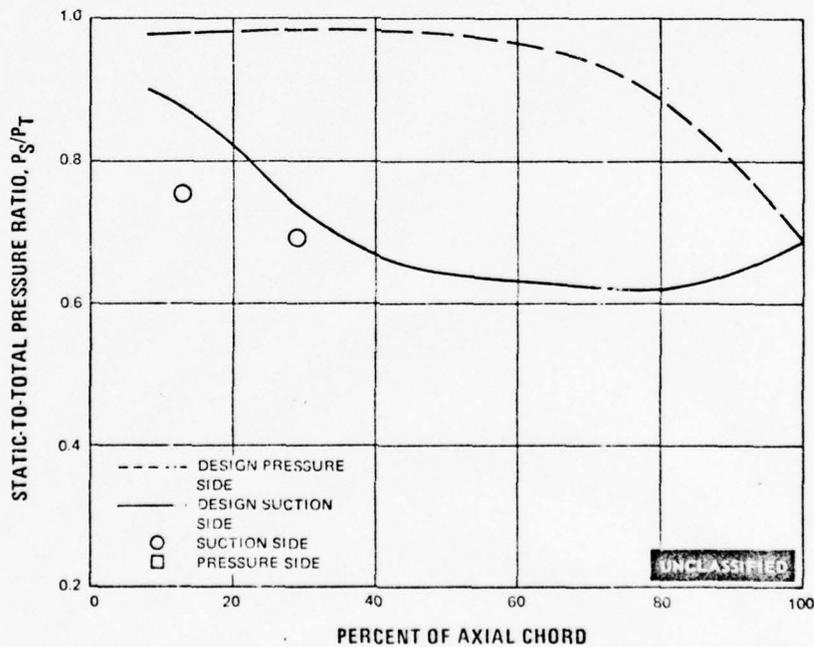


Figure 19 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane With I.D. Roughness and O.D. Flow Fences - Tip Section

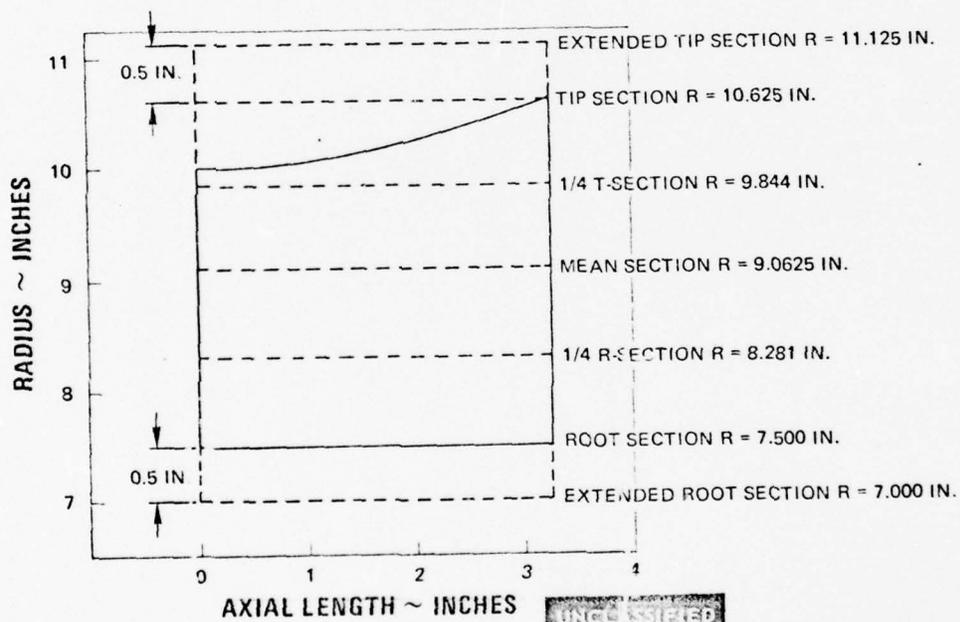
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## 5. BASELINE RETEST WITH REDESIGNED INLET GUIDE VANES

(U) The baseline second vane was retested with redesigned inlet guide vanes. This was necessary since the diagonal wakes from the original inlet guide vanes were interfering with the test airfoil exit plane measurements, as reported in the Reference 3 Report. The elevation and location of each section of the redesigned inlet guide vane is shown in Figure 20, and the sections are presented in Figures 21 through 29. The fabrication coordinates for each section are tabulated in Tables IV through XII in the Appendix.

(U) The performance data for the second vane, normal solidity baseline retest with the redesigned inlet guide vanes are presented in Figures 30 through 35. The inlet guide vane and duct loss is shown in Figure 36. Airfoil surface static pressure distributions at root, mean and tip sections are shown in Figures 37 through 39.



NOTE: SOLID BOUNDARY DEFINES TURNING VANE AIRFLOW PATH

Figure 20 Elevation and Section Location of the Redesigned Second Vane Inlet Guide Vane

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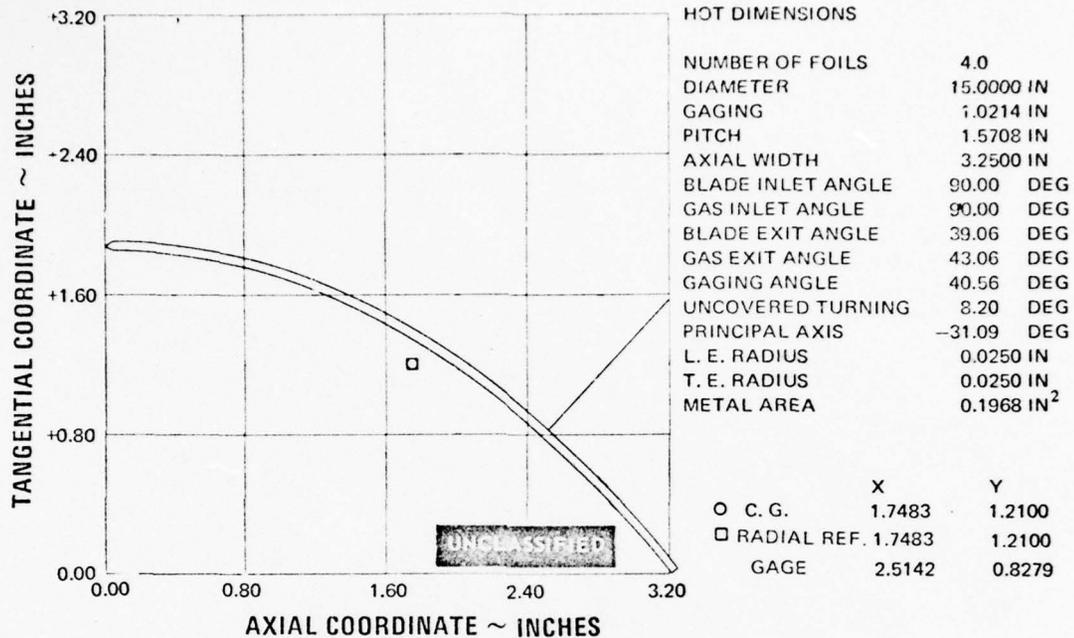


Figure 21 Redesigned Inlet Guide Vane, Second Vane Cascade, Root Section

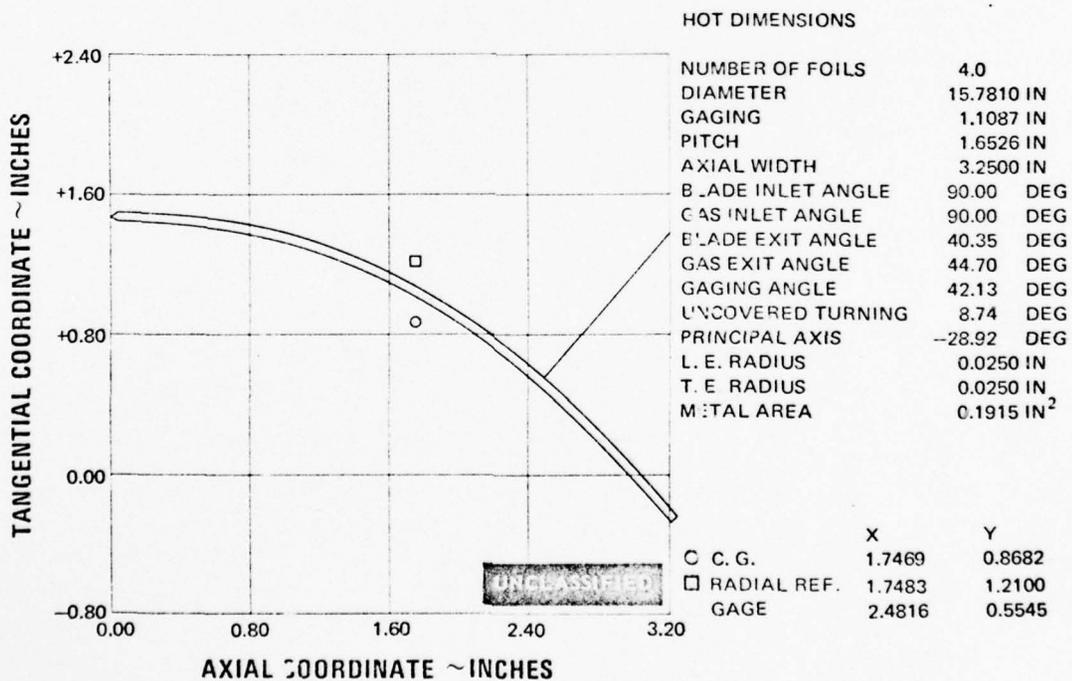


Figure 22 Redesigned Inlet Guide Vane, Second Vane Cascade, 1/8 Root Section

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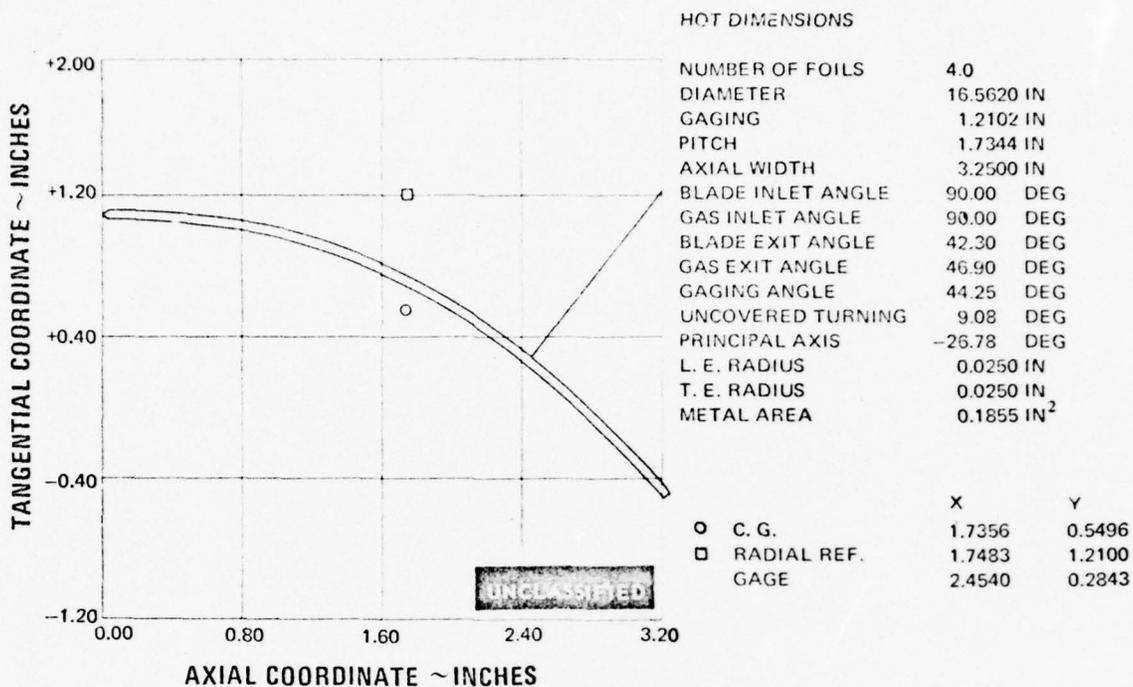


Figure 23 Redesigned Inlet Guide Vane, Second Vane Cascade, 1/4 Root Section

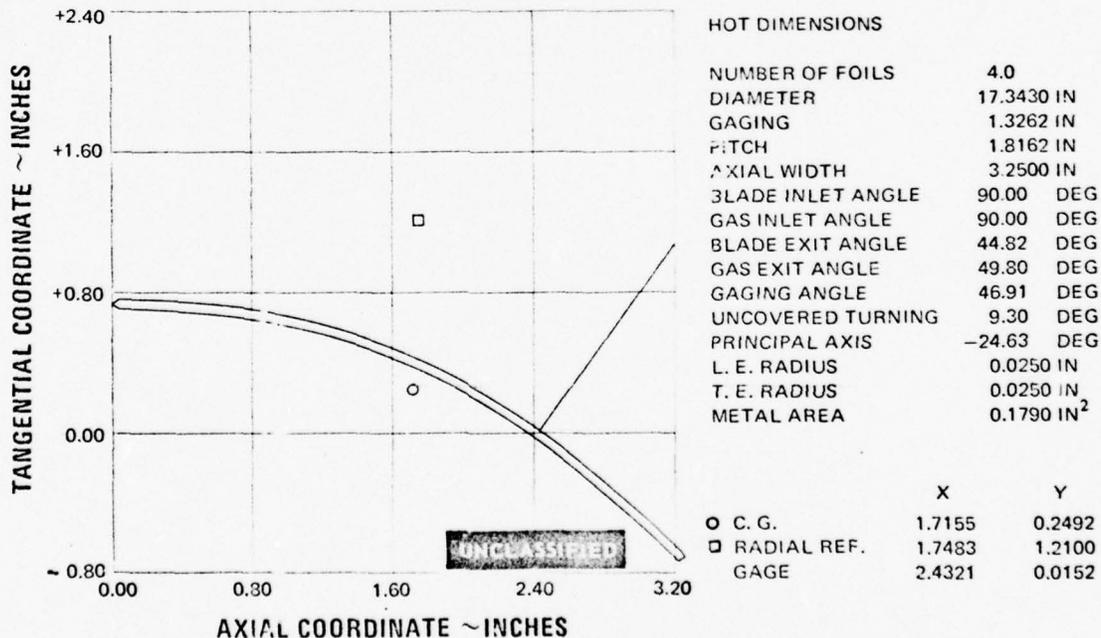


Figure 24 Redesigned Inlet Guide Vane, Second Vane Cascade, 3/8 Root Section

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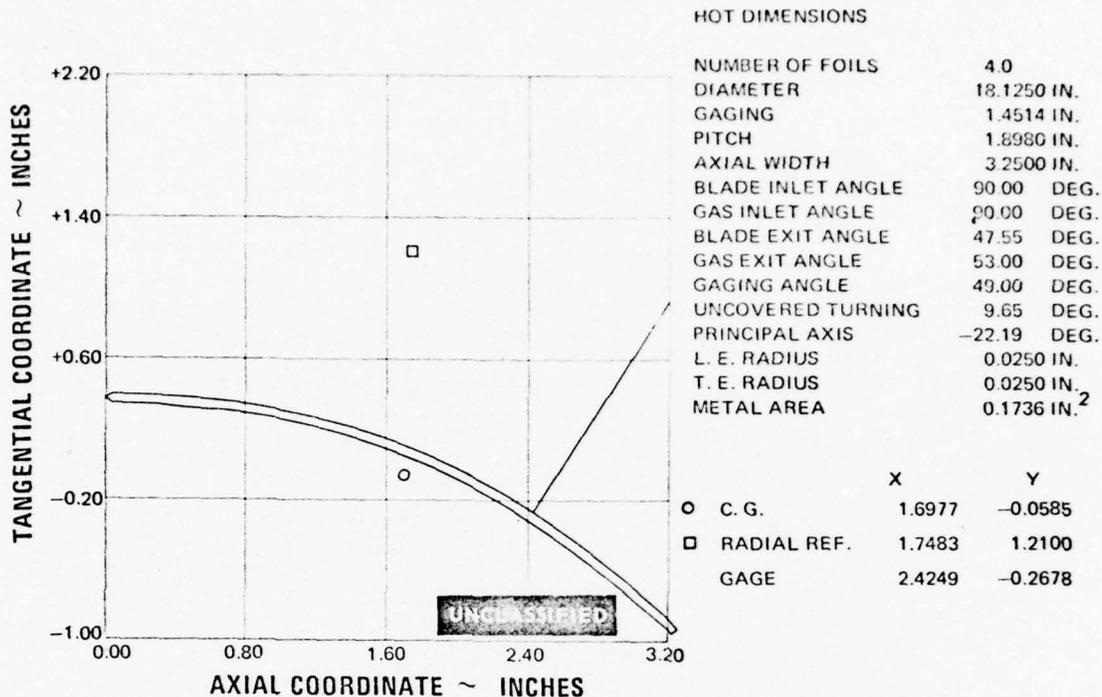


Figure 25 Redesigned Inlet Guide Vane, Second Vane Cascade, Mean Section

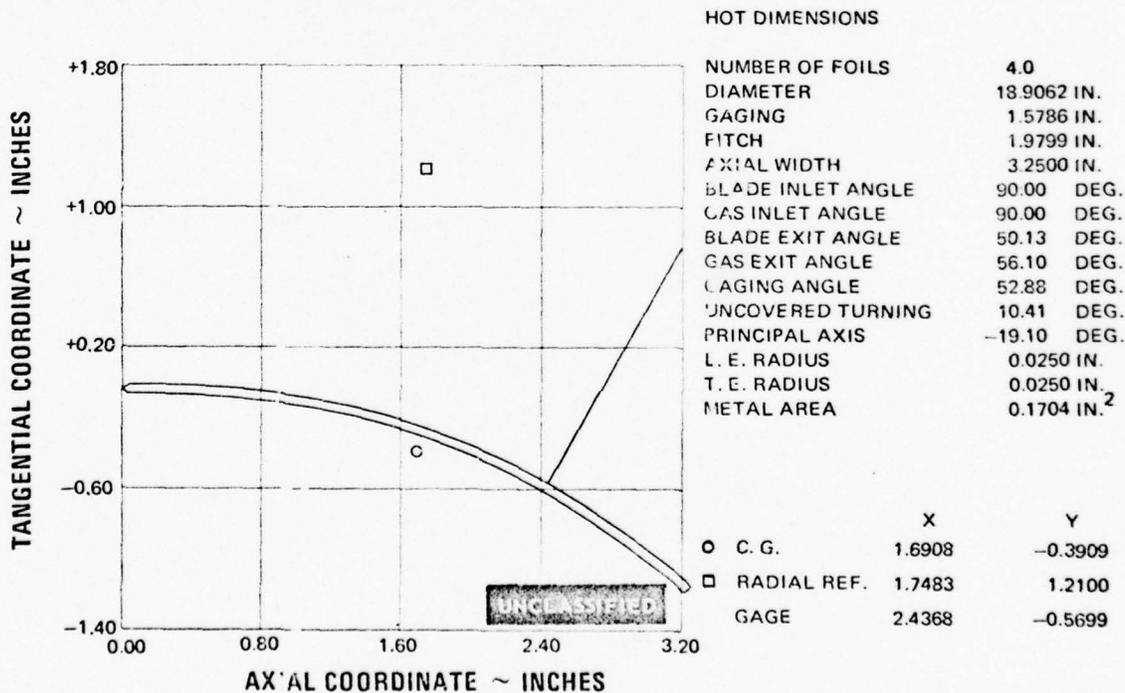


Figure 26 Redesigned Inlet Guide Vane, Second Vane Cascade, 1/8 Tip Section

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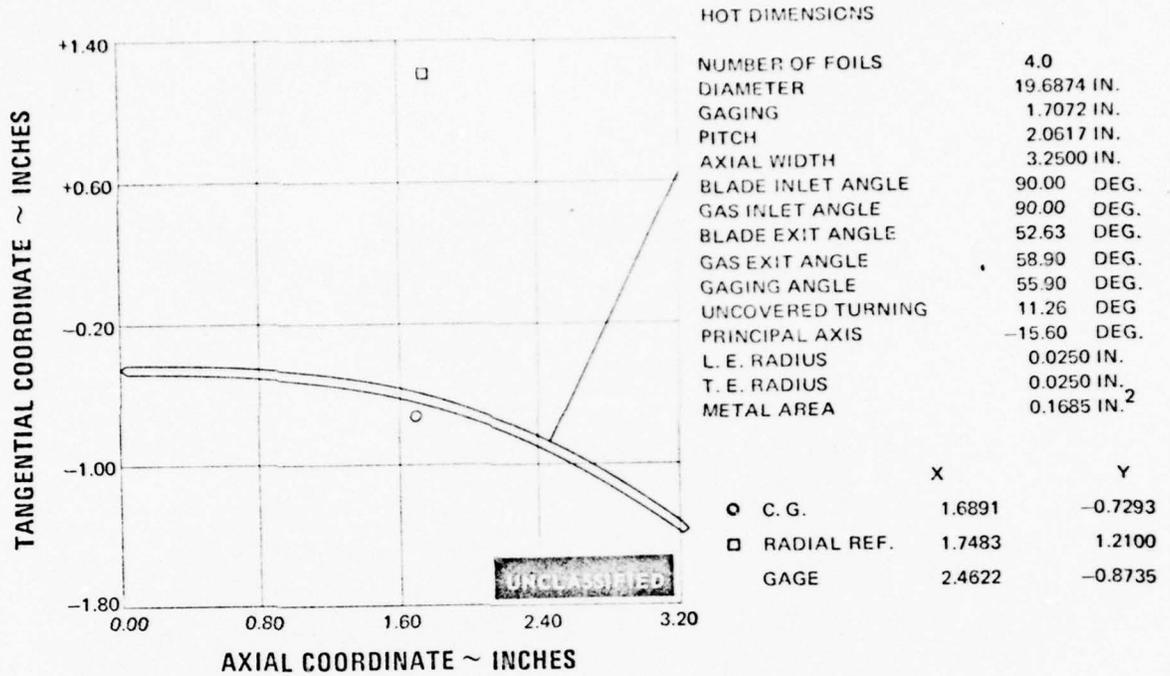


Figure 27 Redesigned Inlet Guide Vane, Second Vane Cascade, 1/4 Tip Section

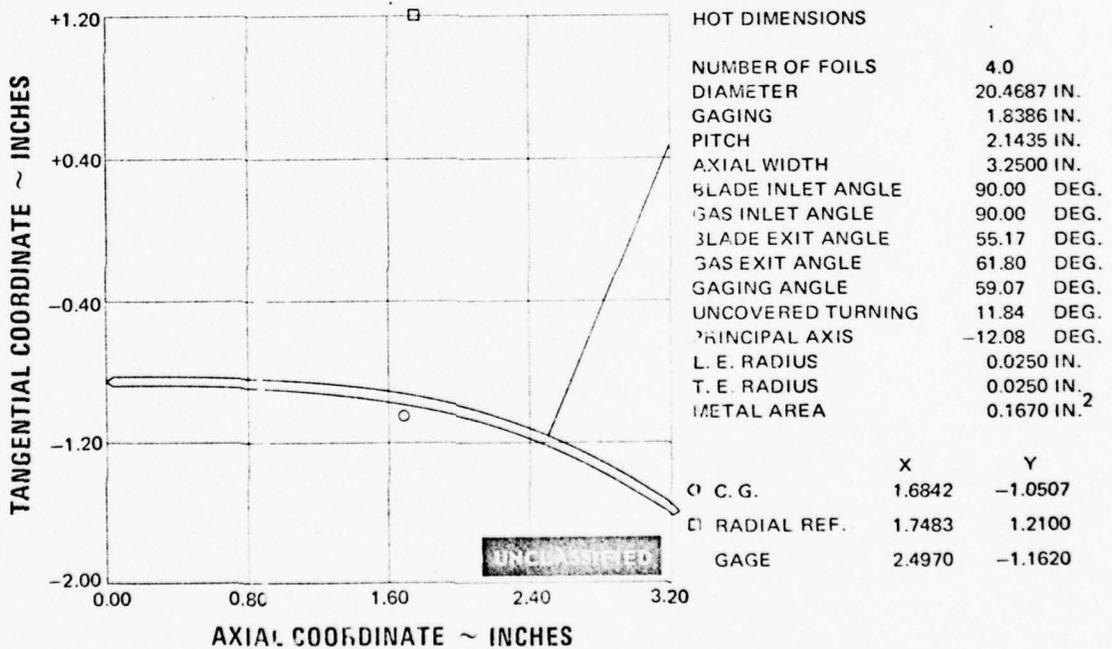


Figure 28 Redesigned Inlet Guide Vane, Second Vane Cascade, 3/8 Tip Section

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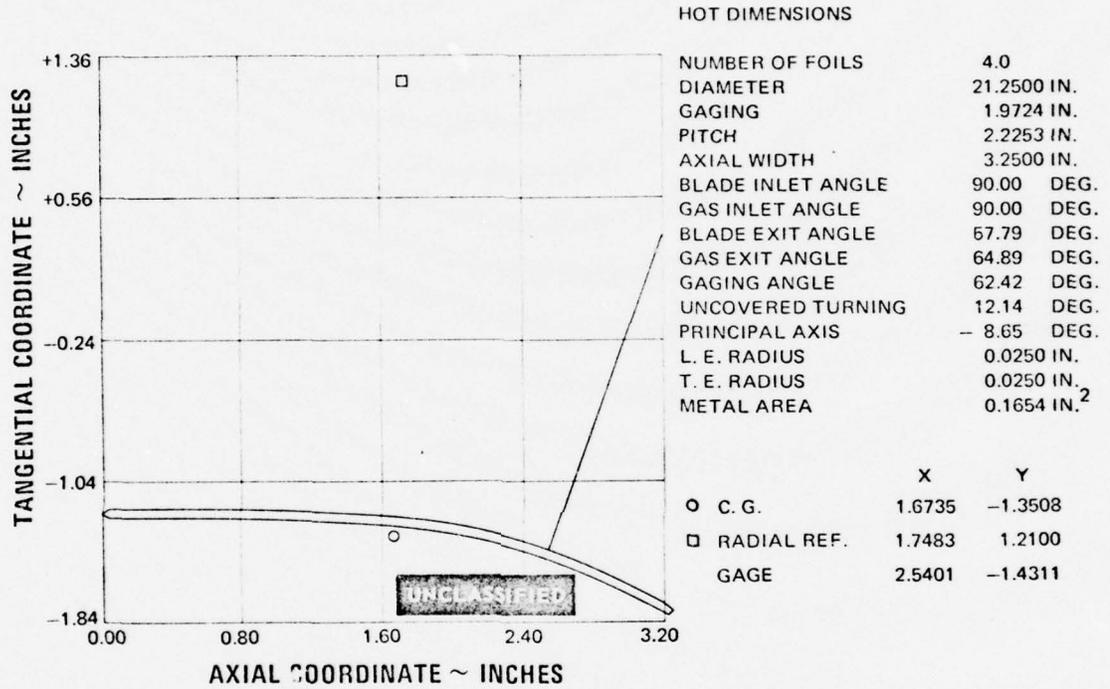


Figure 29 Recesigned Inlet Guide Vane, Second Vane Cascade, Tip Section

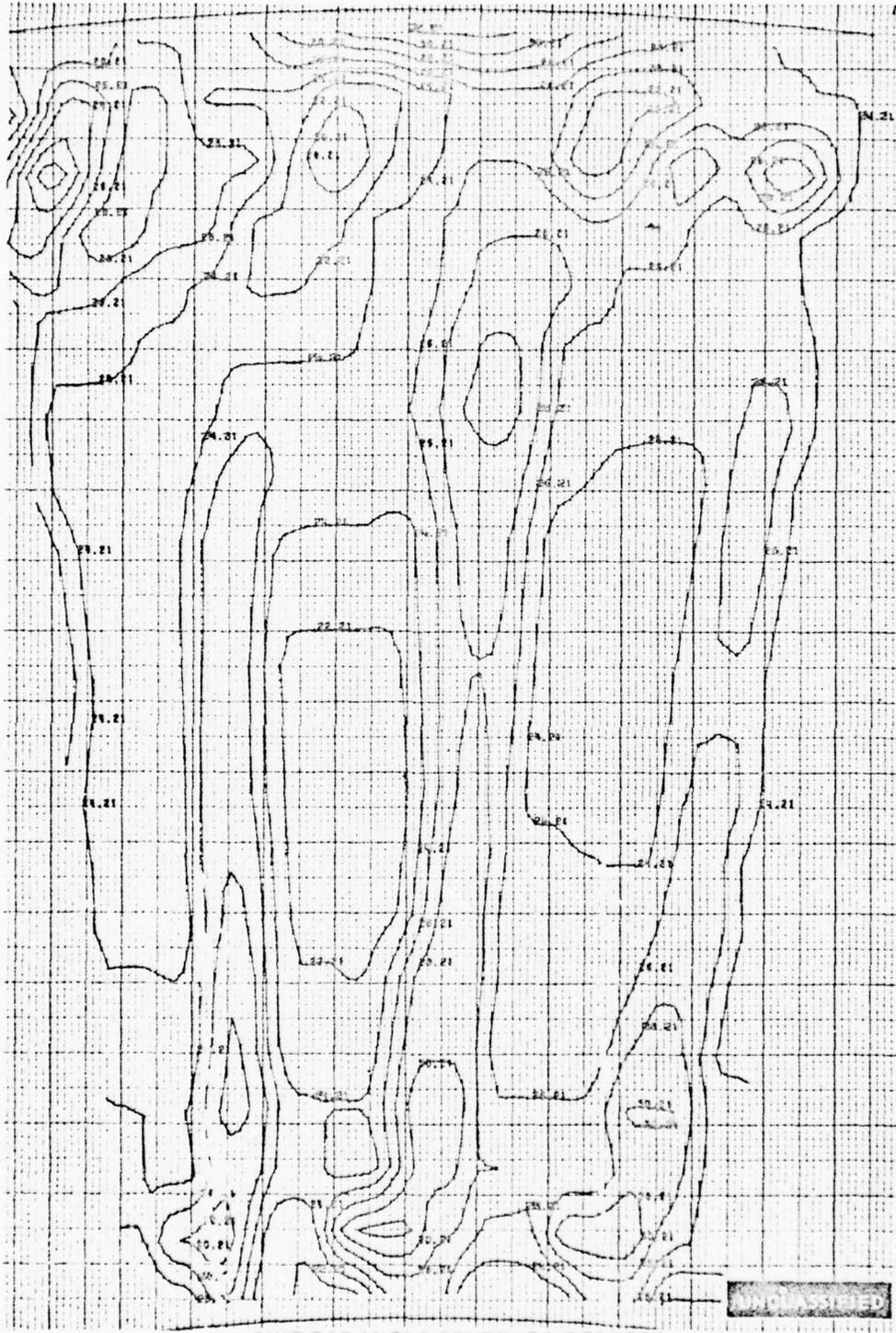
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Figure 30 Pressure Loss Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes

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EXIT GAS ANGLE CONTOURS, DEGREES

Figure 31 Exit Gas Angle Contours. Second Vane - Screen Removed. Three Flow Passages. Midspan Exit Mach No. = 0.912. Baseline With redesigned Inlet Guide Vanes

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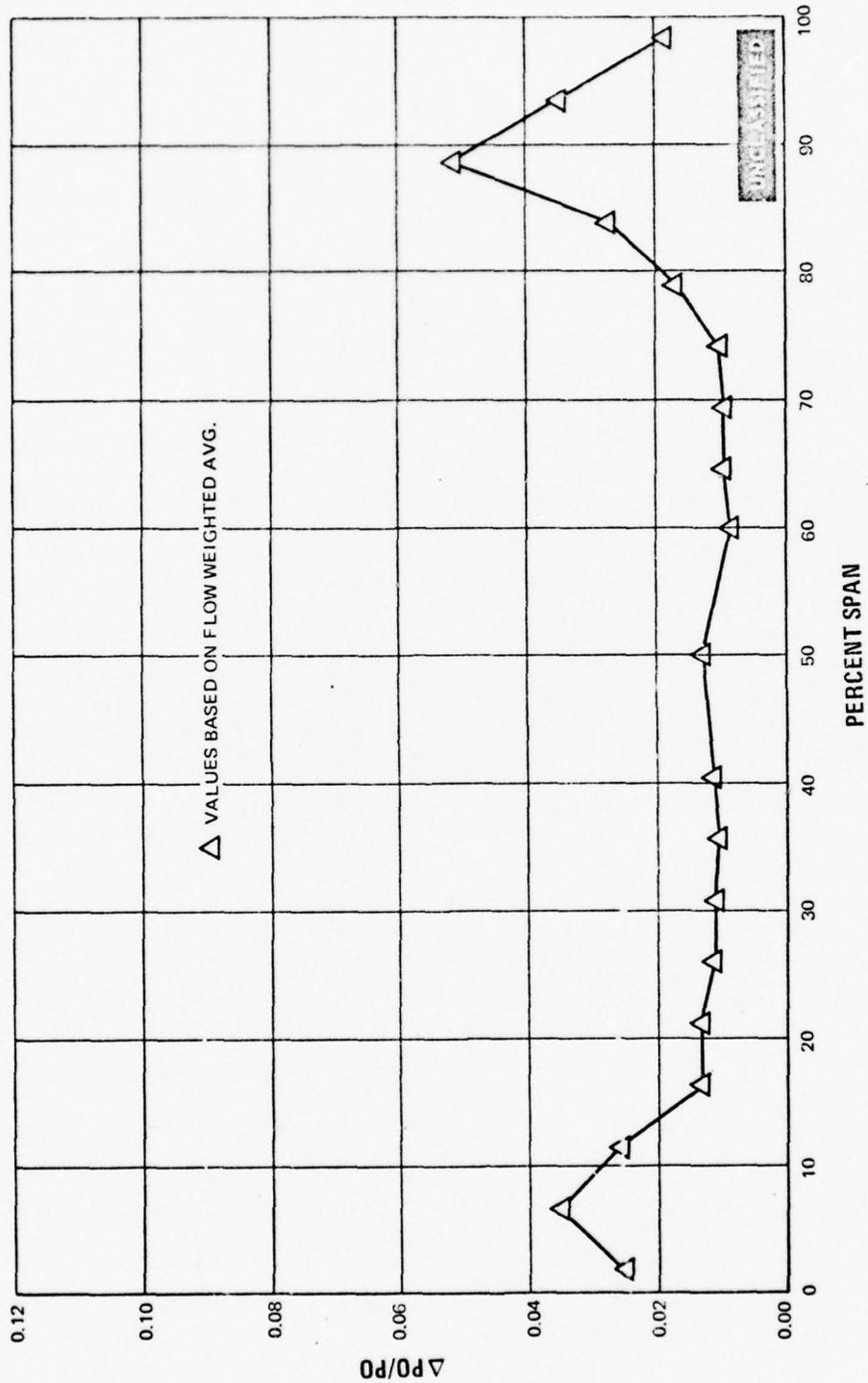


Figure 32 Spanwise Pressure Loss Distribution, Second Vane - Screen Removed, Midspan  
Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes

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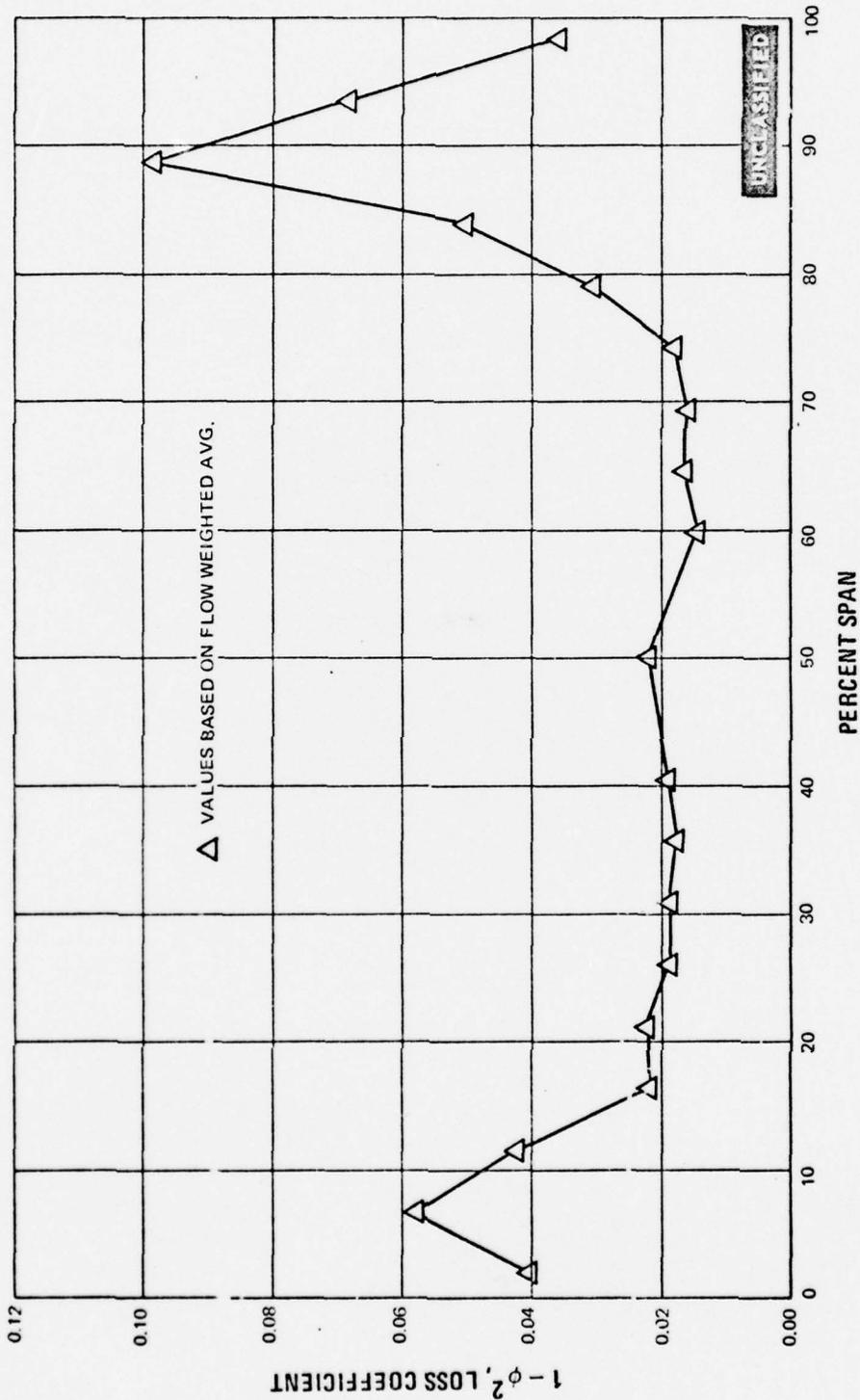


Figure 33 Spanwise Loss Coefficient Distribution, Second vane - Screen Removed, Mid-span Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes

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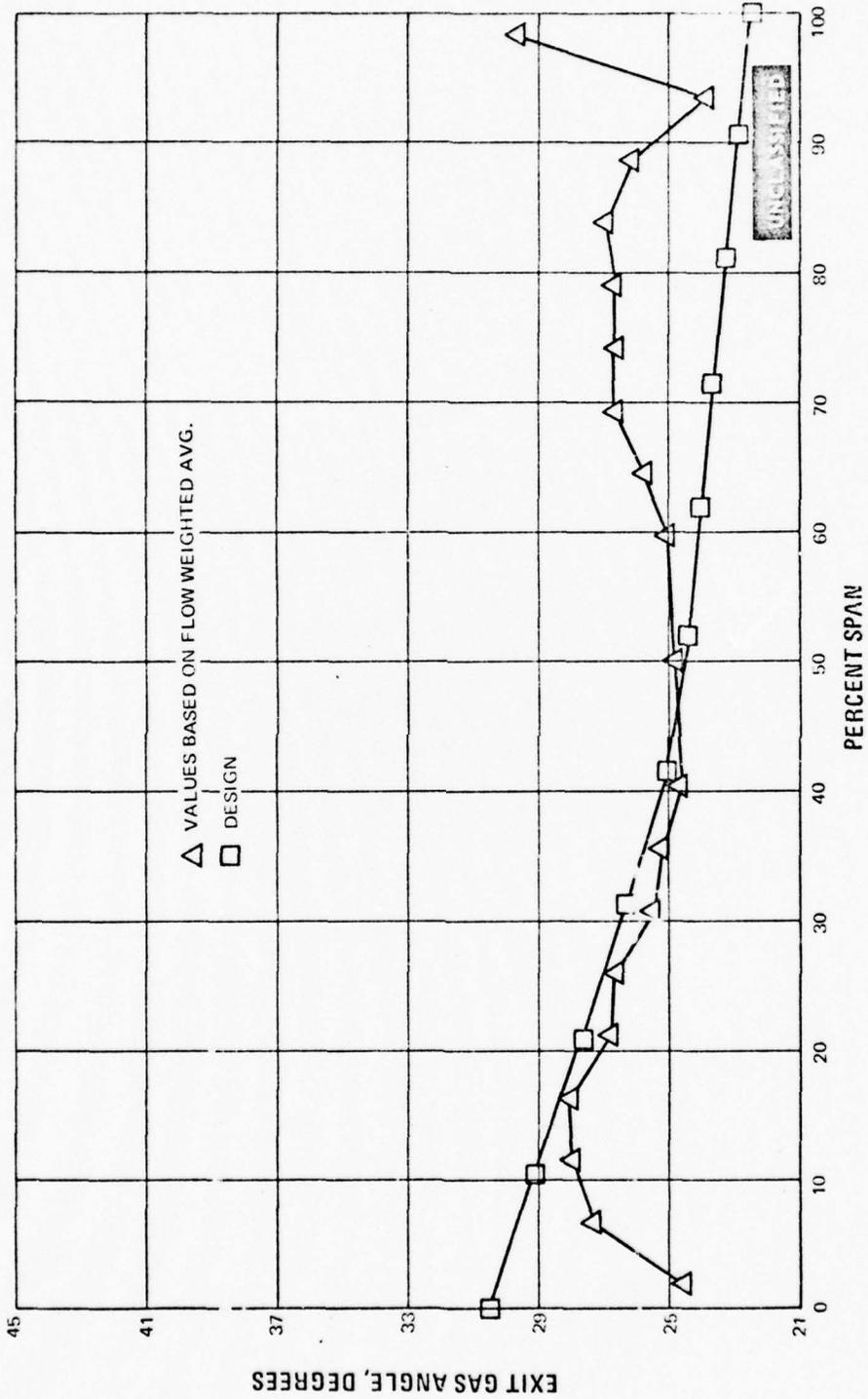


Figure 34 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes

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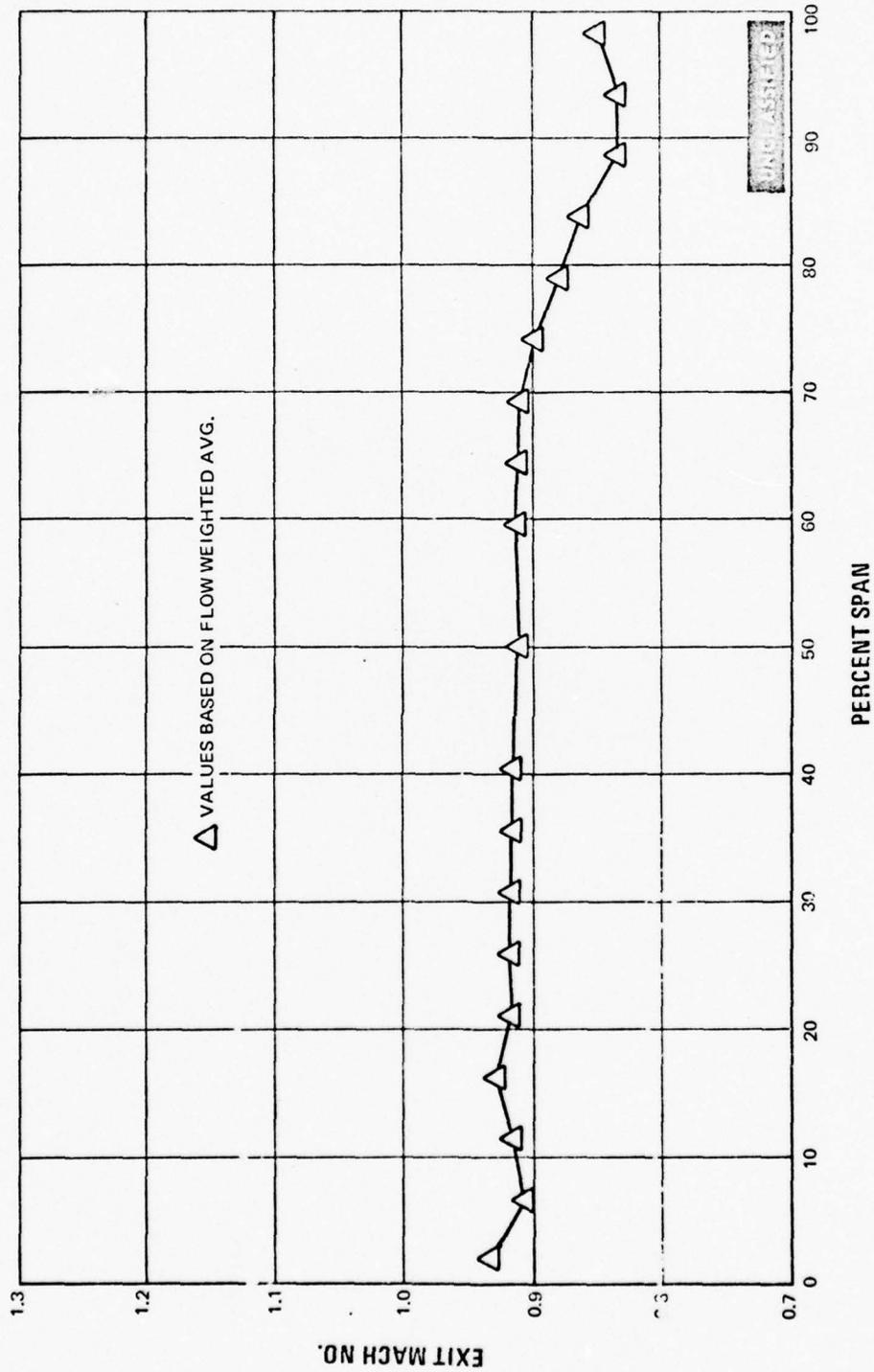


Figure 35 Spanwise Exit Mach Number Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. = 0.912, Baseline With Redesigned Inlet Guide Vanes

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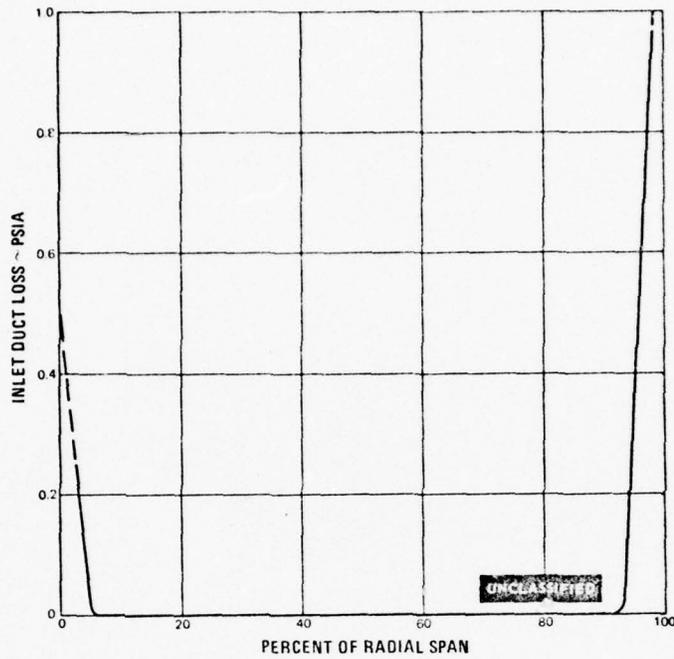


Figure 36 Inlet Duct Loss Versus Percent Radial Span—Second Vane Baseline With Redesigned Inlet Guide Vanes

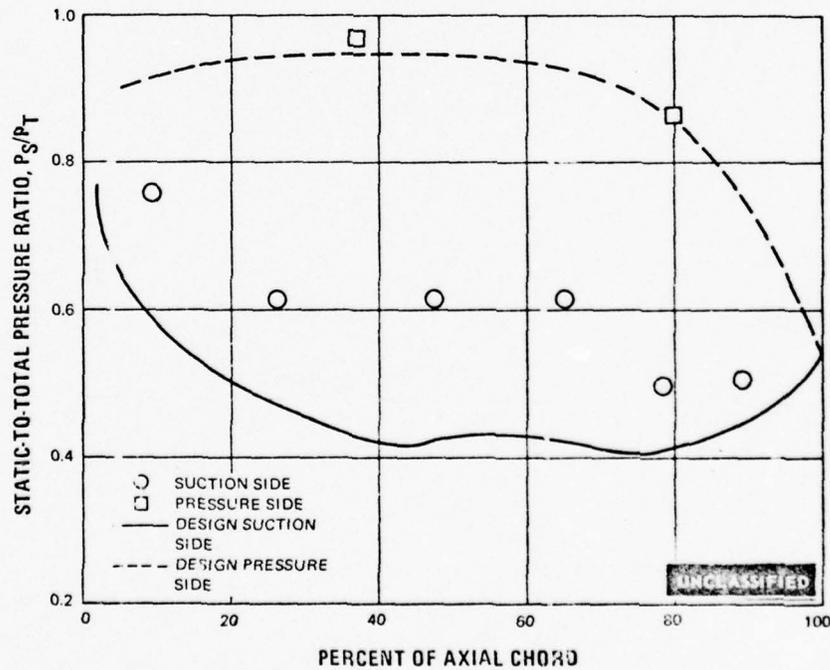


Figure 37 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes—Root Section

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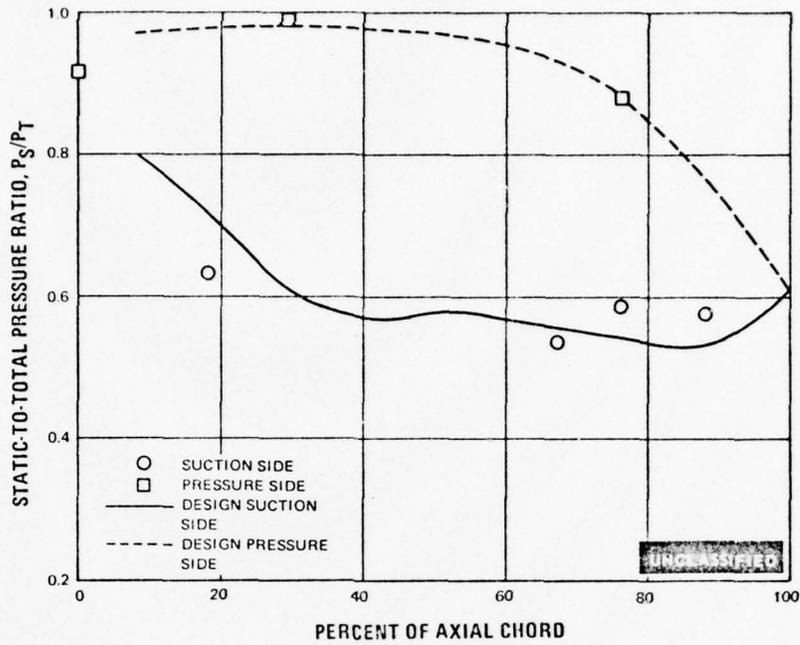


Figure 38 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes - Mean Section

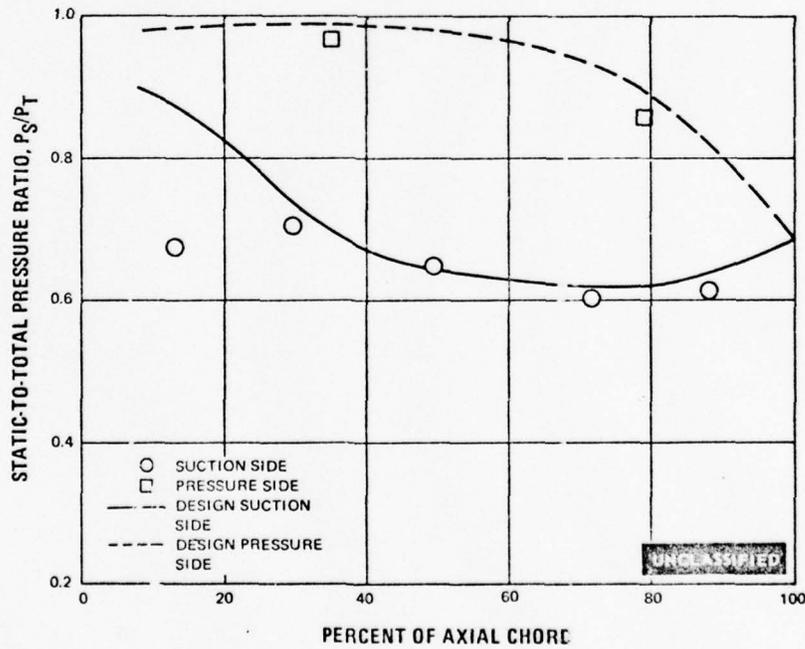


Figure 39 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes - Tip Section

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(U) Analysis of this data indicated that excessive inlet boundary losses were migrating into the test passage due to outside diameter corner boundary layer separation and secondary flow currents within the inlet guide vane channels. This can be clearly seen on the total pressure loss contour maps (Figure 30), where pockets of large losses are seen at the outside portion of the test airfoil channel. To correct this, boundary layer bleed slots were cut into the inlet guide vane pack inside-diameter and outside-diameter walls. The slots were cut close to the inlet guide vane, along the full length of the chord, on the acute angle side of the passage. Initially, a 0.125 inch wide slot was cut at the outside-diameter, and a 0.094 inch slot at the inside-diameter.

(U) This baseline second vane cascade, with the redesigned inlet guide vanes and the boundary layer bleeds was tested in the annular segment cascade. The performance data is presented in Figures 40 through 45. The inlet duct loss with the boundary layer bleeds is indicated in Figure 46. The airfoil surface statics are shown in Figures 47 through 49. Analysis of this data with the boundary layer bleeds showed significant improvement of the pressure loss contours at the end-walls, especially at the tip section. The cascade was free of inlet guide vane wakes and end-wall losses over all of the span with the exception of a small region at the inside diameter wall, which had a slight disturbance. Furthermore, oil and graphite flow visualization tests were made on the test airfoils and these are shown in Figures 50 through 53. These indicate attached flow over the airfoil with some radial inflow at the endwalls.

(U) A photograph of the patterns on the inlet guide vane suction surface is shown in Figure 54. It can be observed from this photograph that there was a strong tendency for radial flow toward the bleed slots along the guide vanes. Consequently, a program to minimize the boundary layer bleed slots, in order to maintain the lowest bleed flow and still prevent the accumulation of losses due to the inlet duct boundary layer separation, was undertaken.

(U) As a result of this program, it was found that the outside diameter boundary layer bleeds could be reduced from 0.125 to 0.047 inch in width and still prevent inlet duct boundary layer effects on the test airfoils. The inside diameter slots were not changed. The performance data of the baseline cascade with these "optimum" bleeds are shown in Figures 55 through 60. The inlet guide vane and duct loss with the optimum bleeds is shown in Figure 61. Analysis of these data indicated a shift of the baseline loss coefficients to a slightly lower level, compared to the original baseline data without bleeds. Extremely thorough checks of hardware, instrumentation and data did not resolve the data shift. To verify the accuracy of the optimum bleed test, this test was rerun and the lower loss level was repeated. The reason for the lower loss level is probably due to a lower turbulence intensity of the flow as seen by the test airfoil; this lower turbulence resulting from the bleeding of inlet boundary layer.

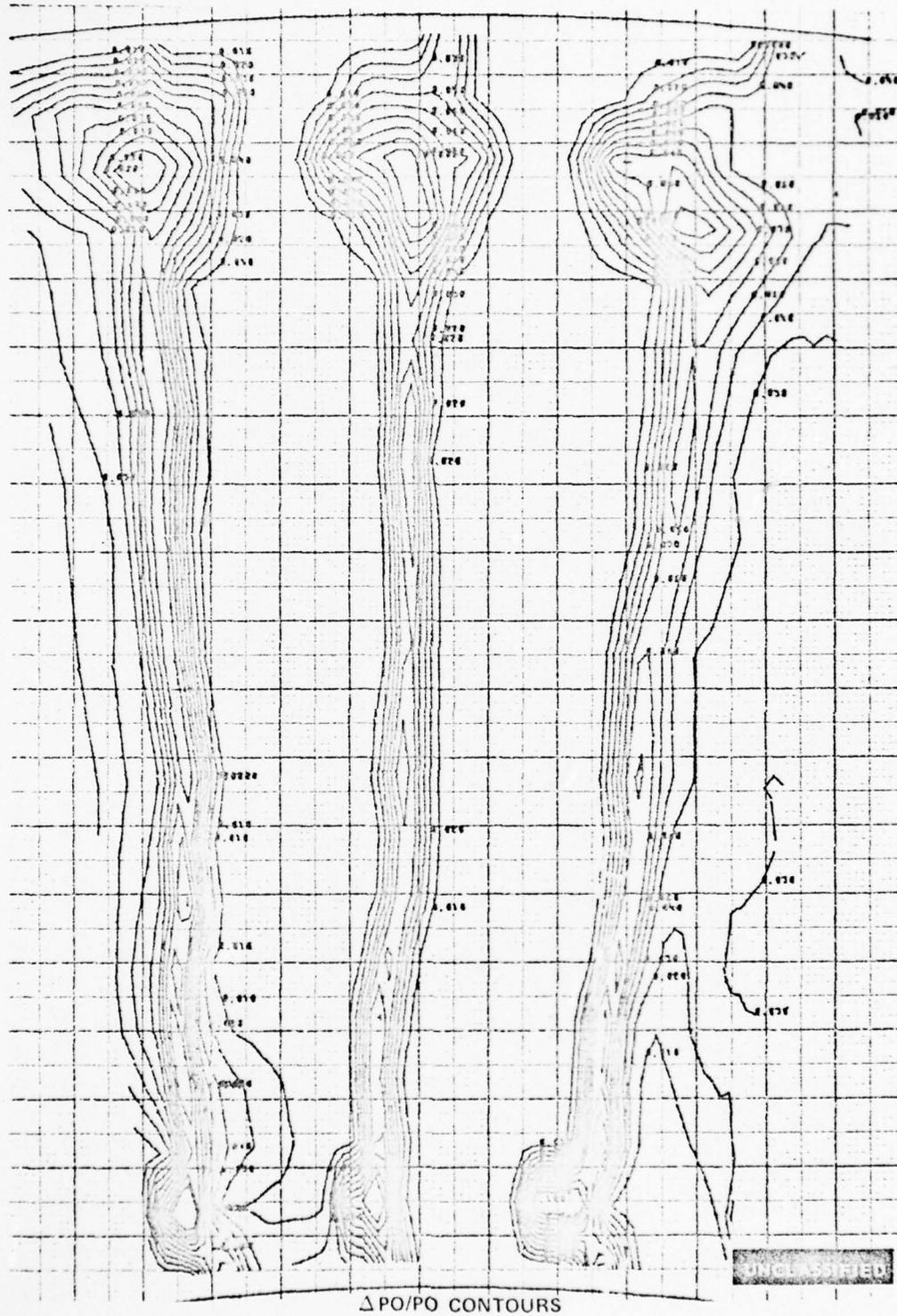


Figure 40 Pressure Loss Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

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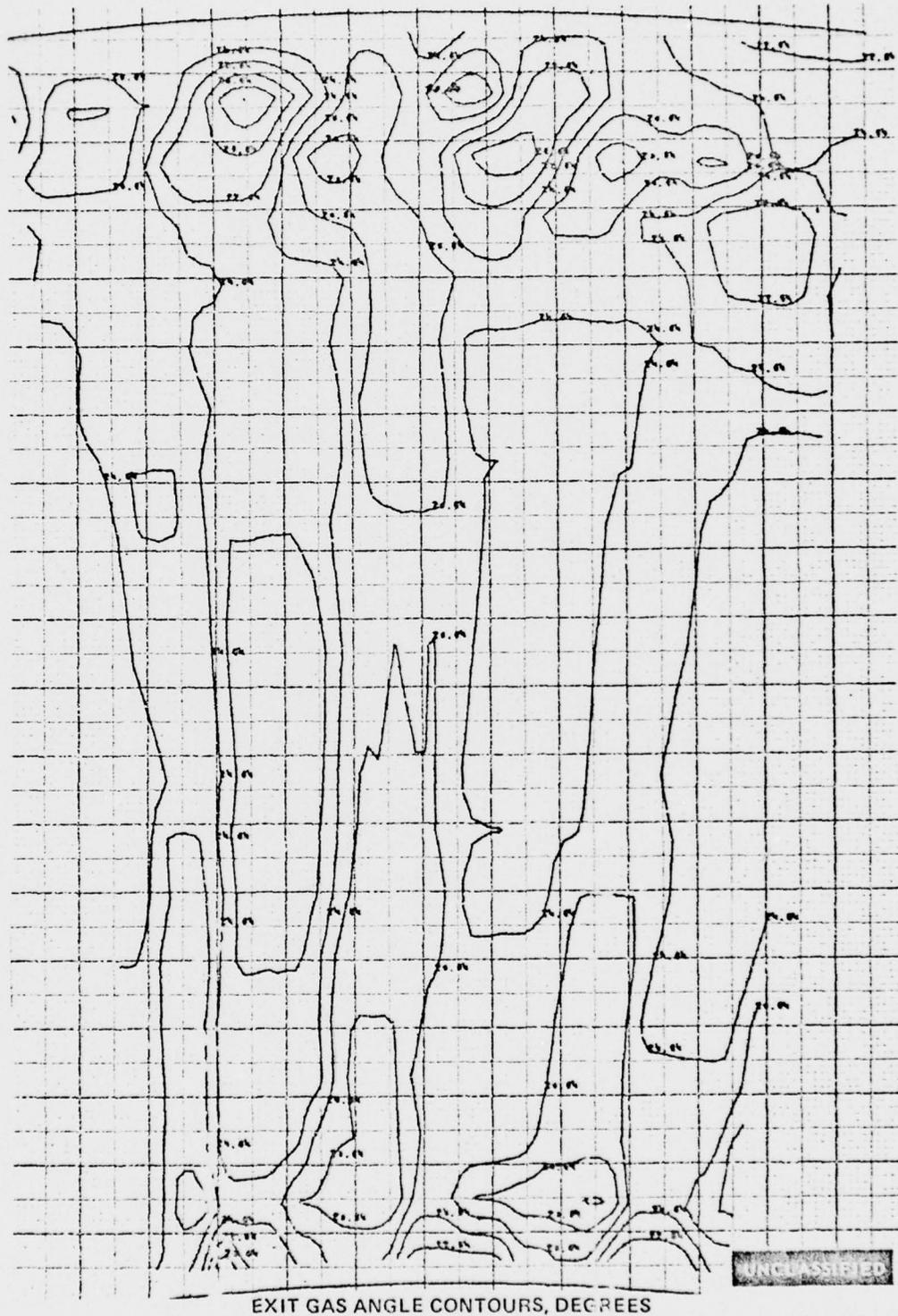


Figure 41 Exit Gas Angle Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

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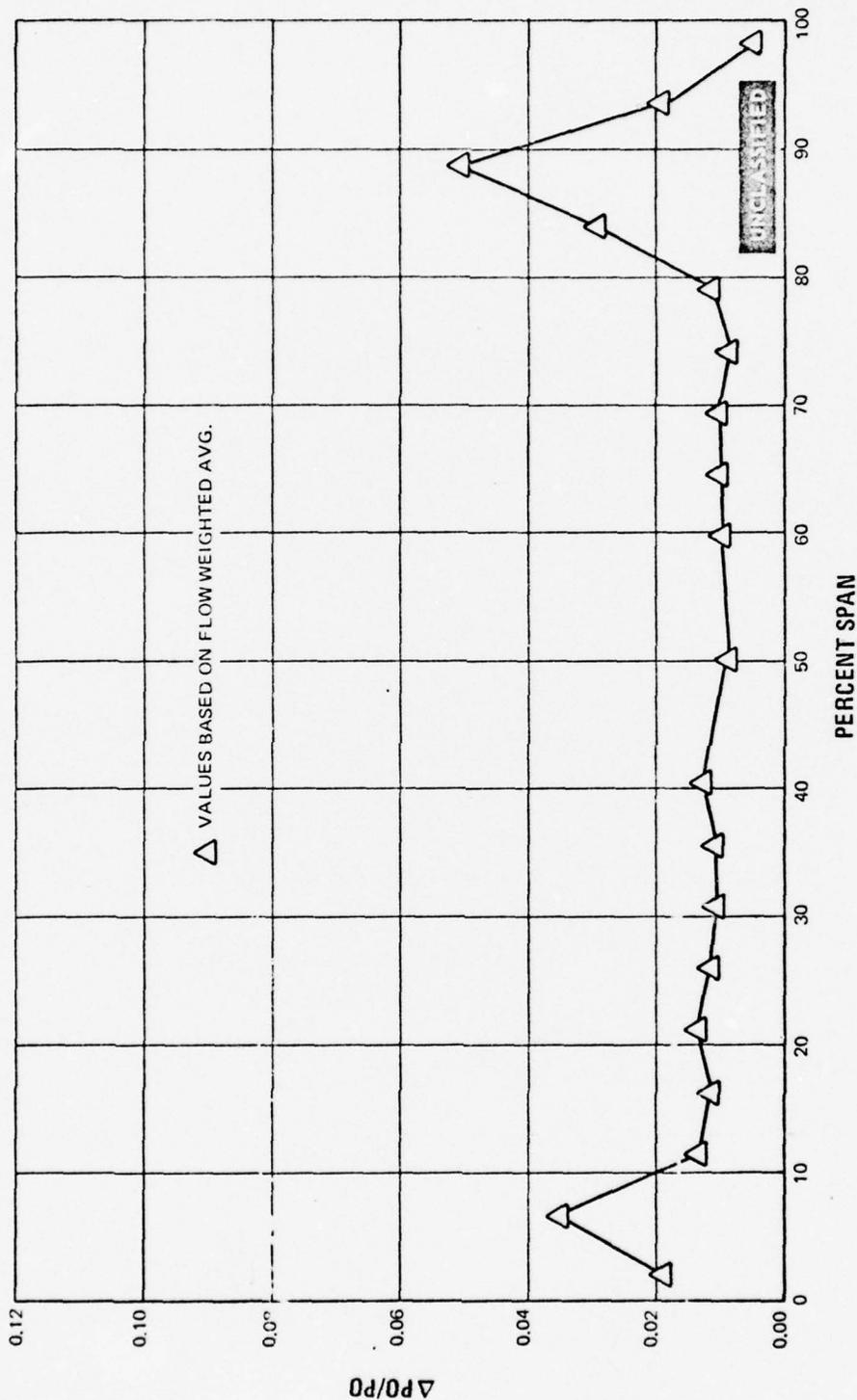


Figure 42 Spanwise Pressure Loss Distribution, Second Vane - Screen Removed, Midspan  
Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

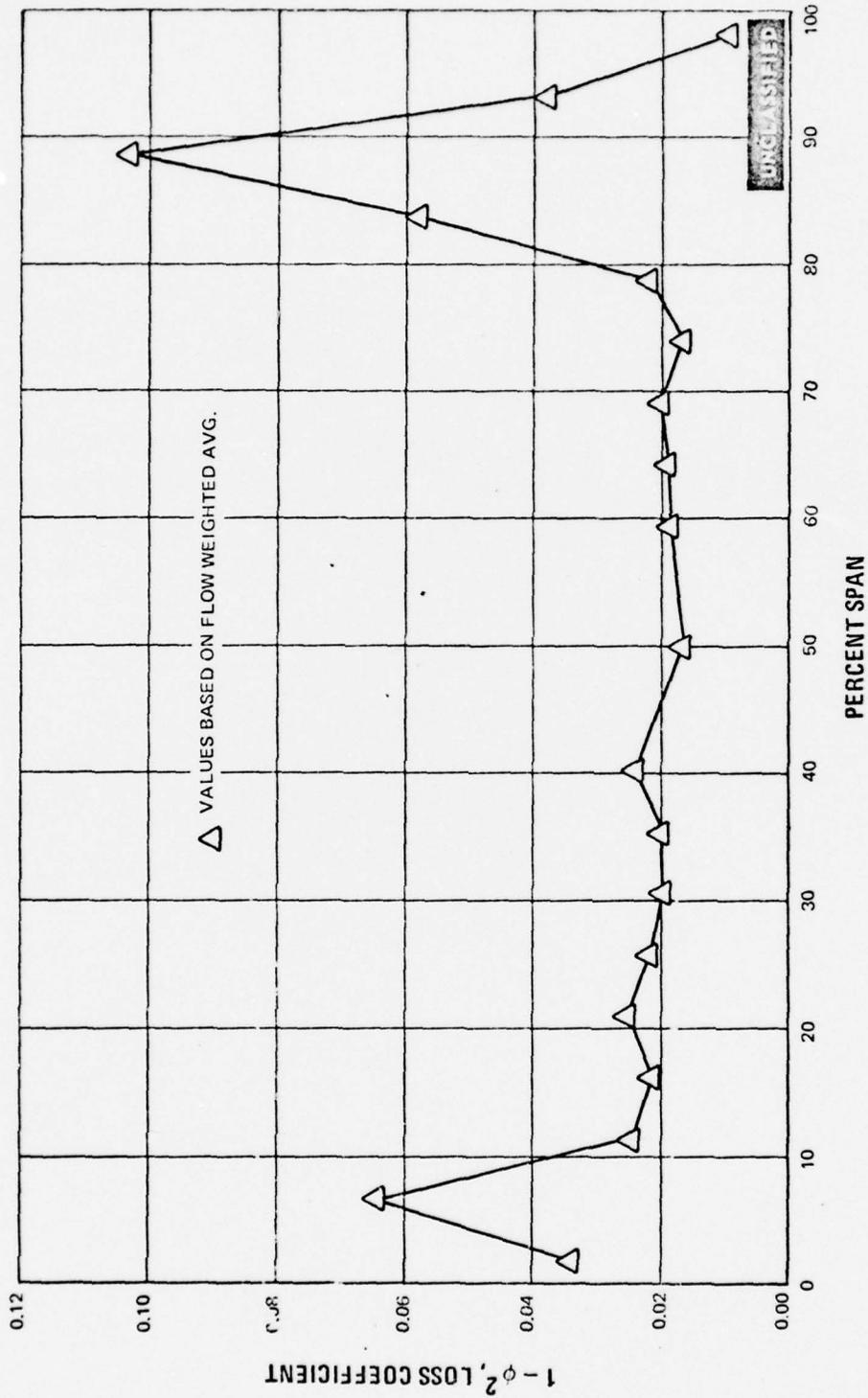


Figure 43 Spanwise Loss Coefficient Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

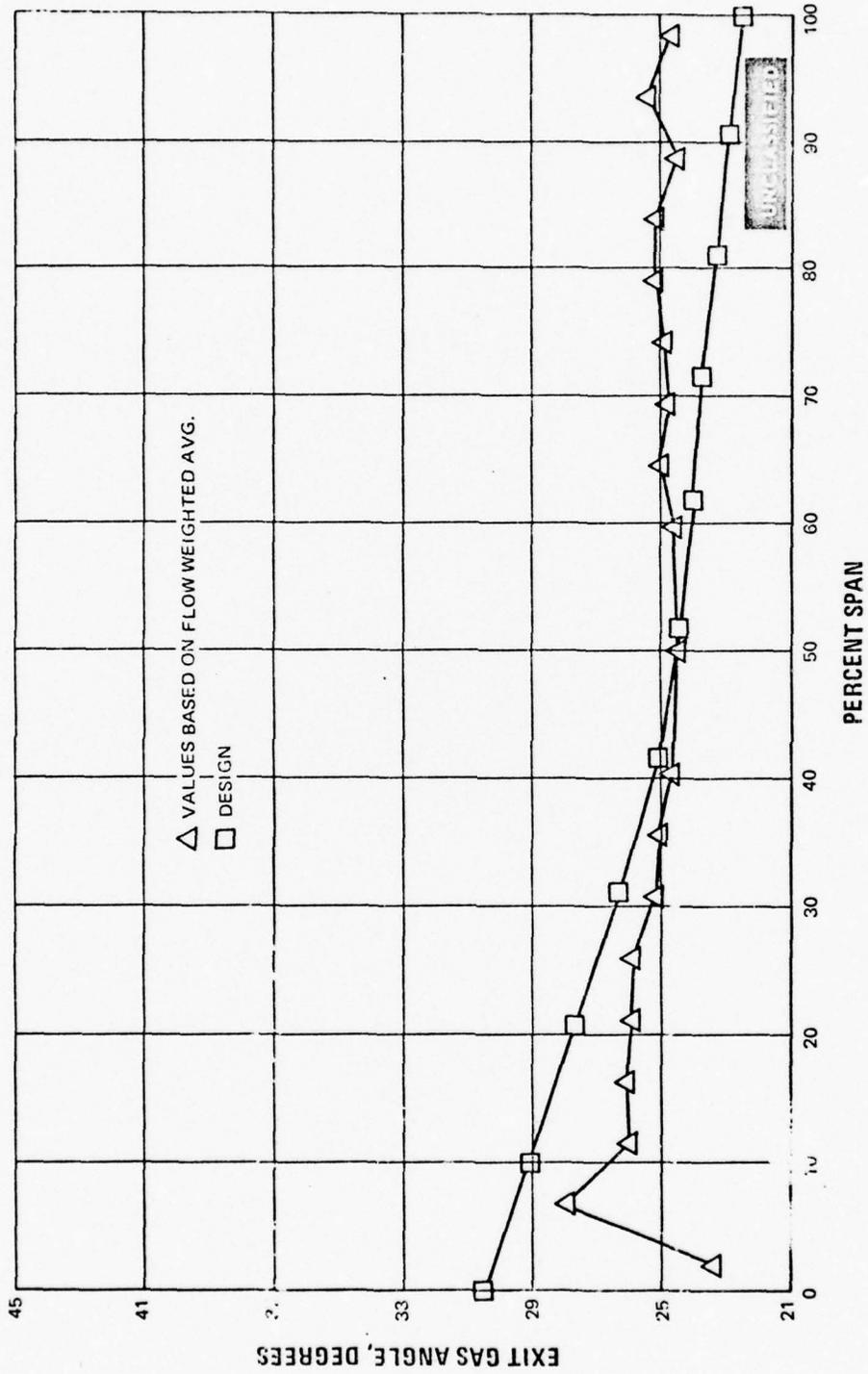


Figure 44 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

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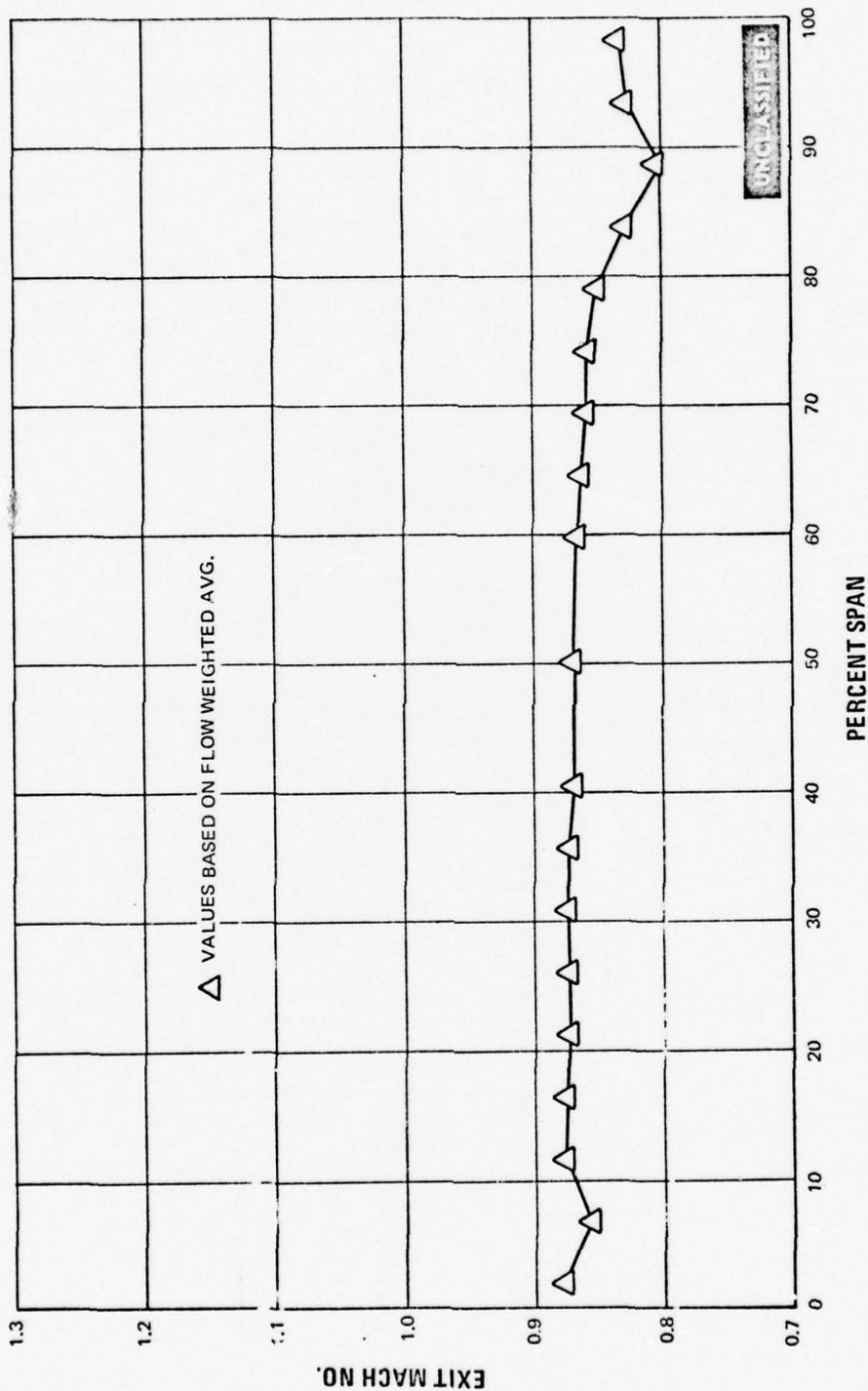


Figure 45 Spanwise Exit Mach Number Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. = 0.869, Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds

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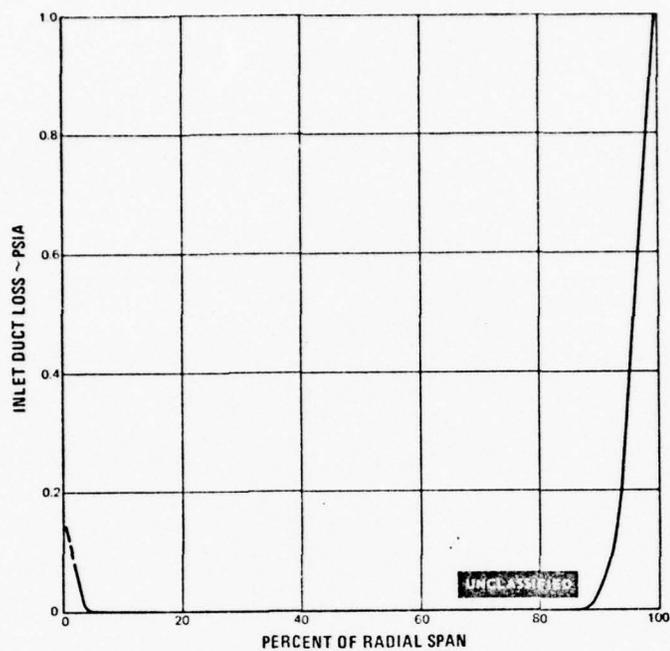


Figure 46 Inlet Duct Loss Versus Percent Radial Span—Second Vane Cascade With Re-designed Inlet Guide Vanes and Boundary Layer Bleeds

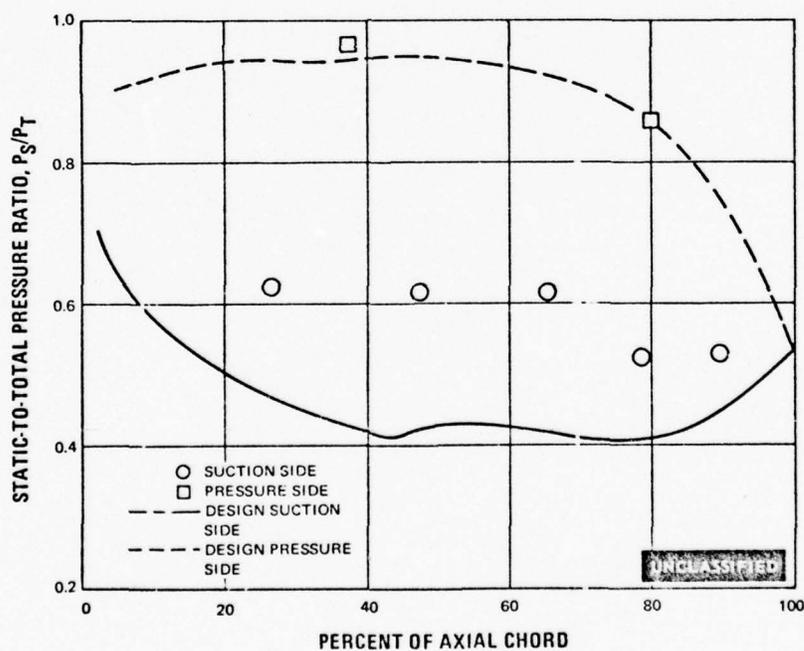


Figure 47 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds—Root Section

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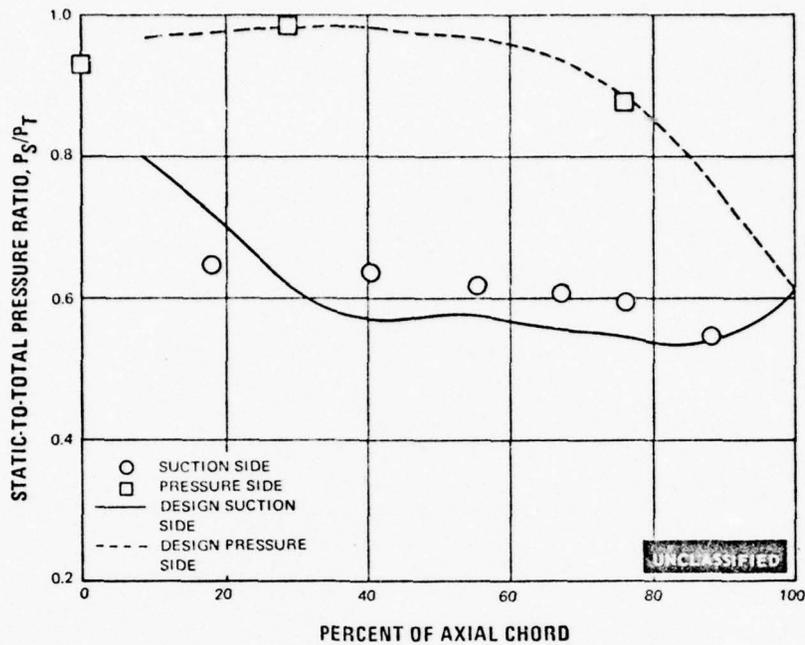


Figure 48 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds—Mean Section

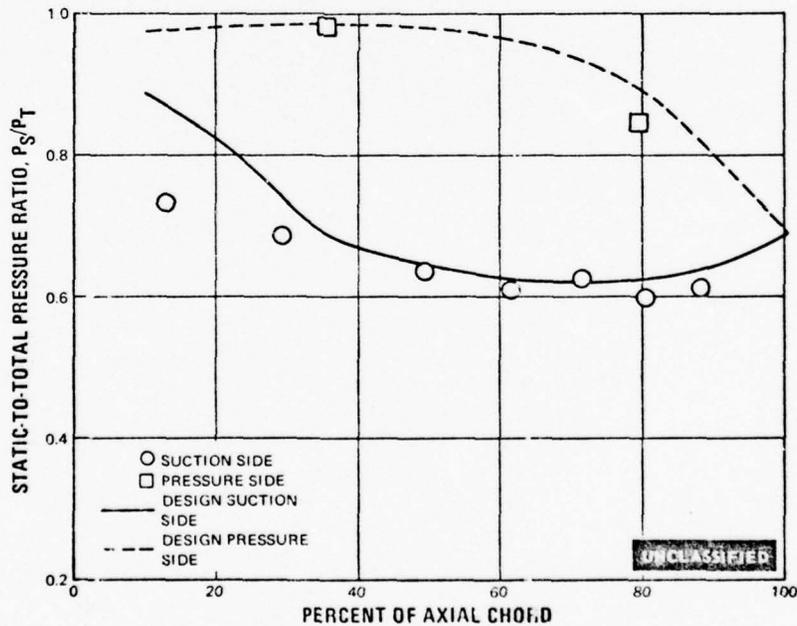


Figure 49 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes and Boundary Layer Bleeds—Tip Section

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Figure 50 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Upstream Inside Diameter; Midspan Exit Mach No. =0.87



Figure 51 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Outside Diameter; Midspan Exit Mach No. =0.87

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Figure 52 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Inside Diameter; Midspan Exit Mach No. =0.87



Figure 53 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes and Original Boundary Layer Bleed Slots; View of Downstream Outside Diameter; Midspan Exit Mach No. =0.87

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Figure 54 Oil and Graphite Flow Patterns Inlet Guide Vane with Original Boundary Layer Bleed Slots; Midspan Exit Mach No. = 0.87

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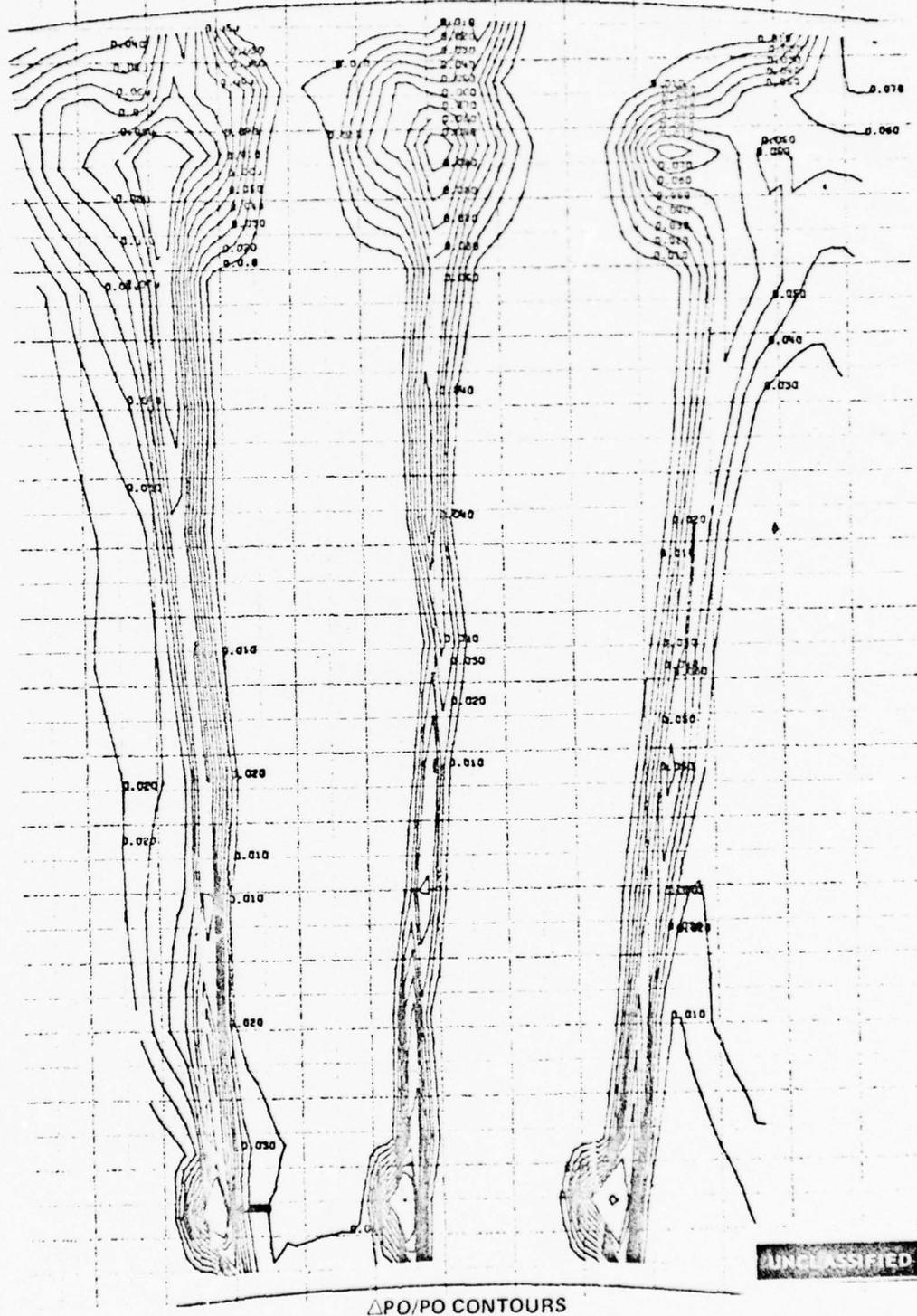


Figure 55 Pressure Loss Contours, Second Vane - Screen Removed. Three Flow Passages. Midspan Exit Mach No. = 0.885. Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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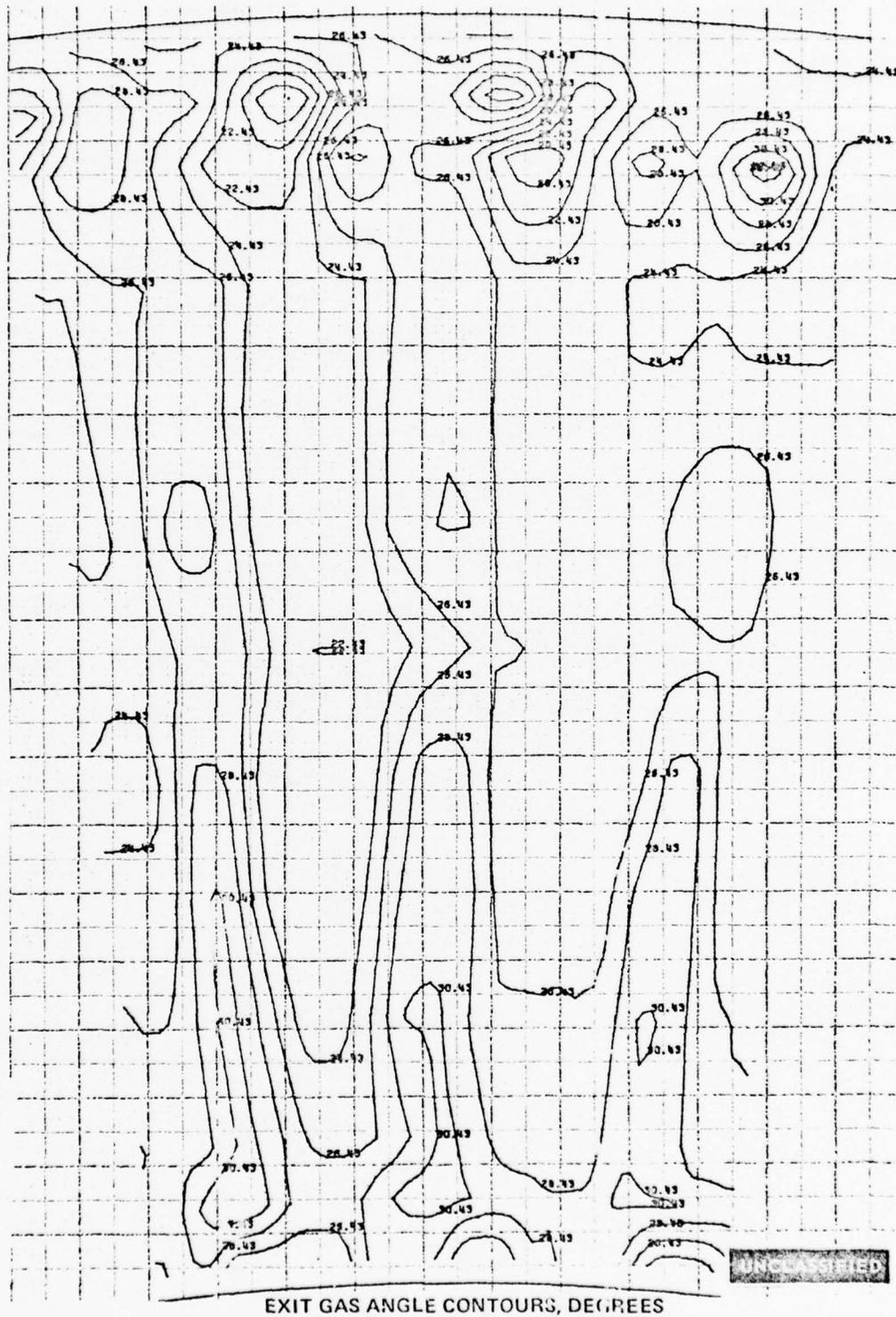


Figure 56 Exit Gas Angle Contours, Second Vane - Screen Removed, Three Flow Passages, Midspan Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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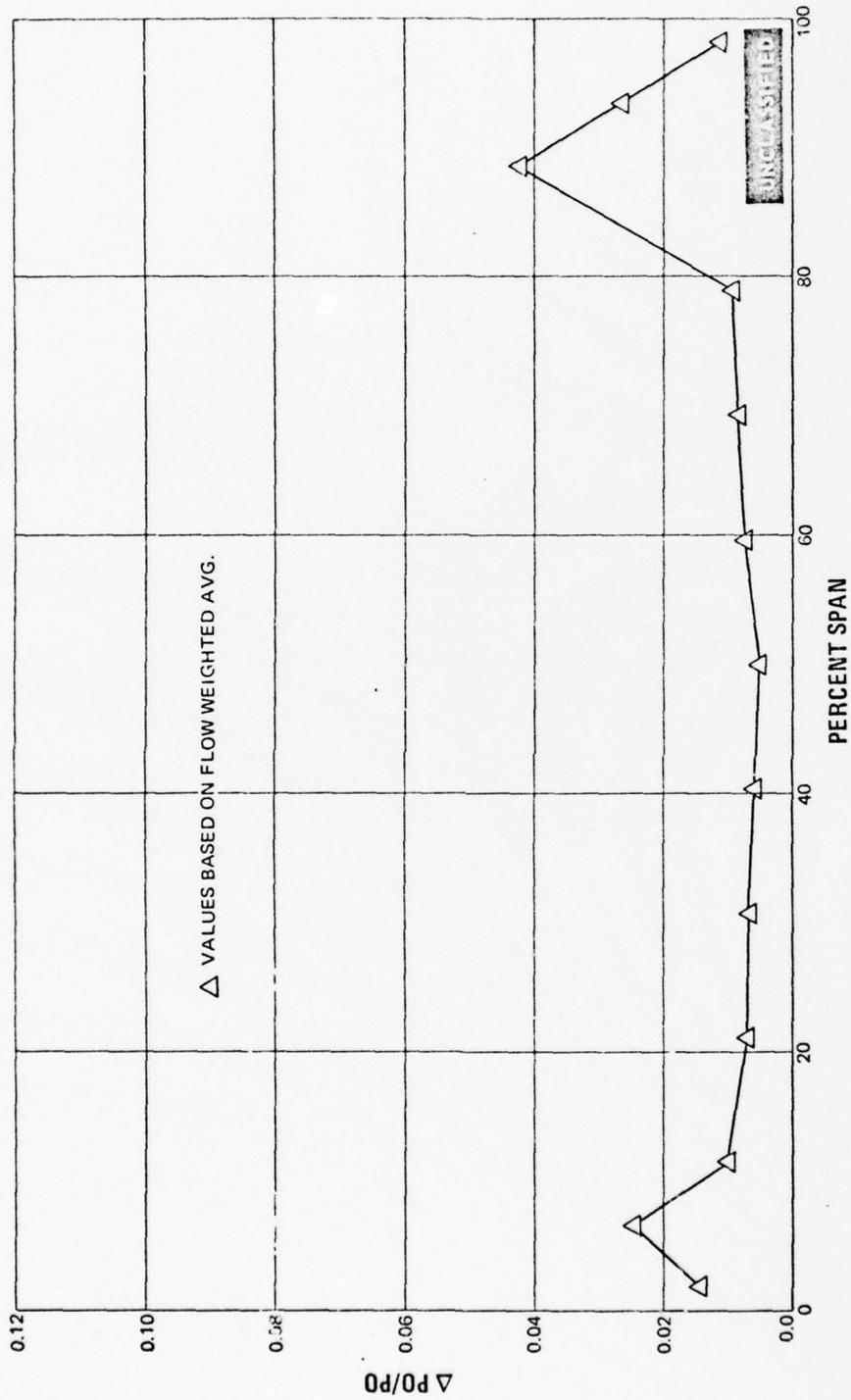


Figure 57 Spanwise Pressure Loss Distribution, Second Vane - Screen Removed, Midspan  
Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and  
Optimum Boundary Layer Bleeds

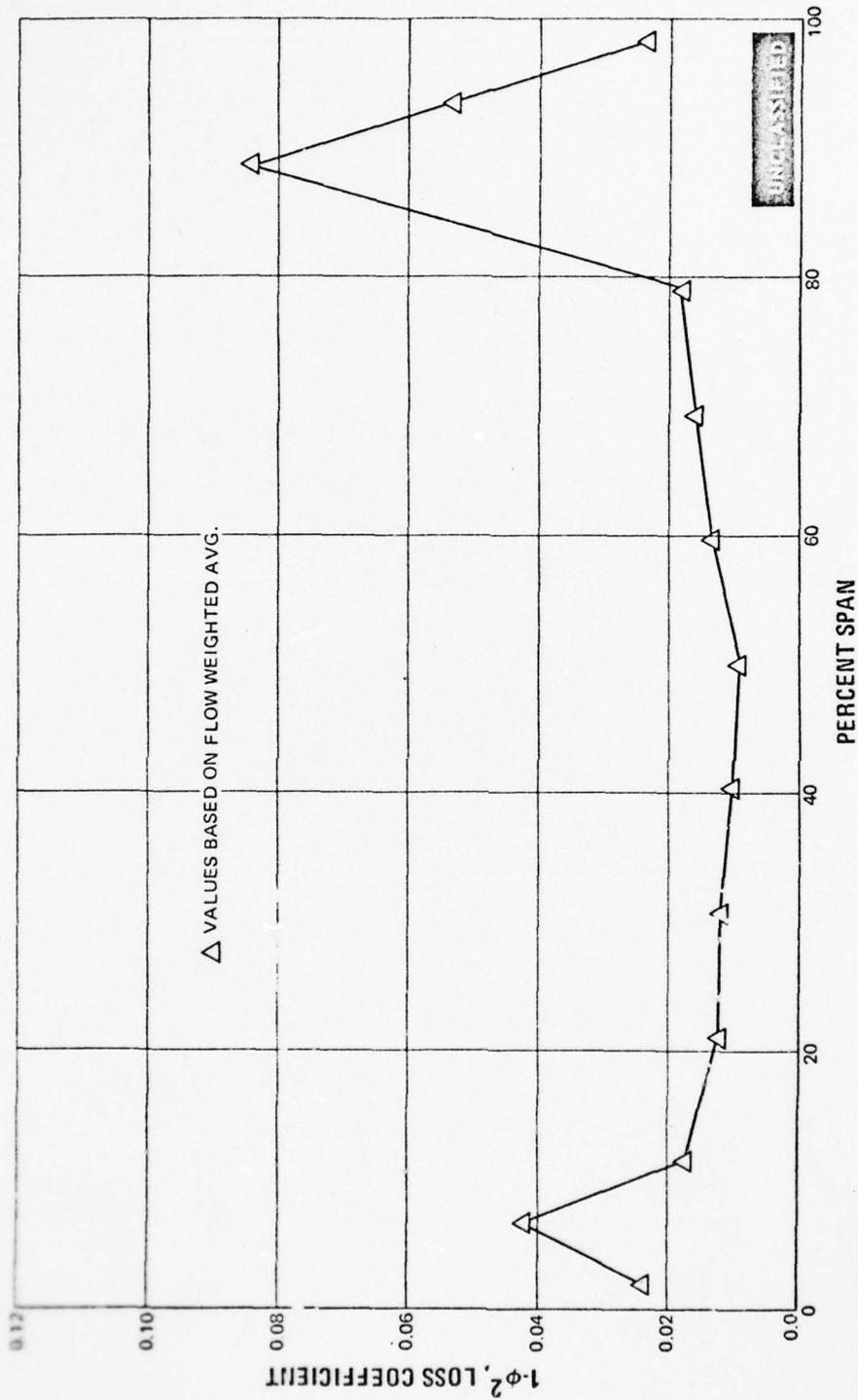


Figure 58 Spanwise Loss Coefficient Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

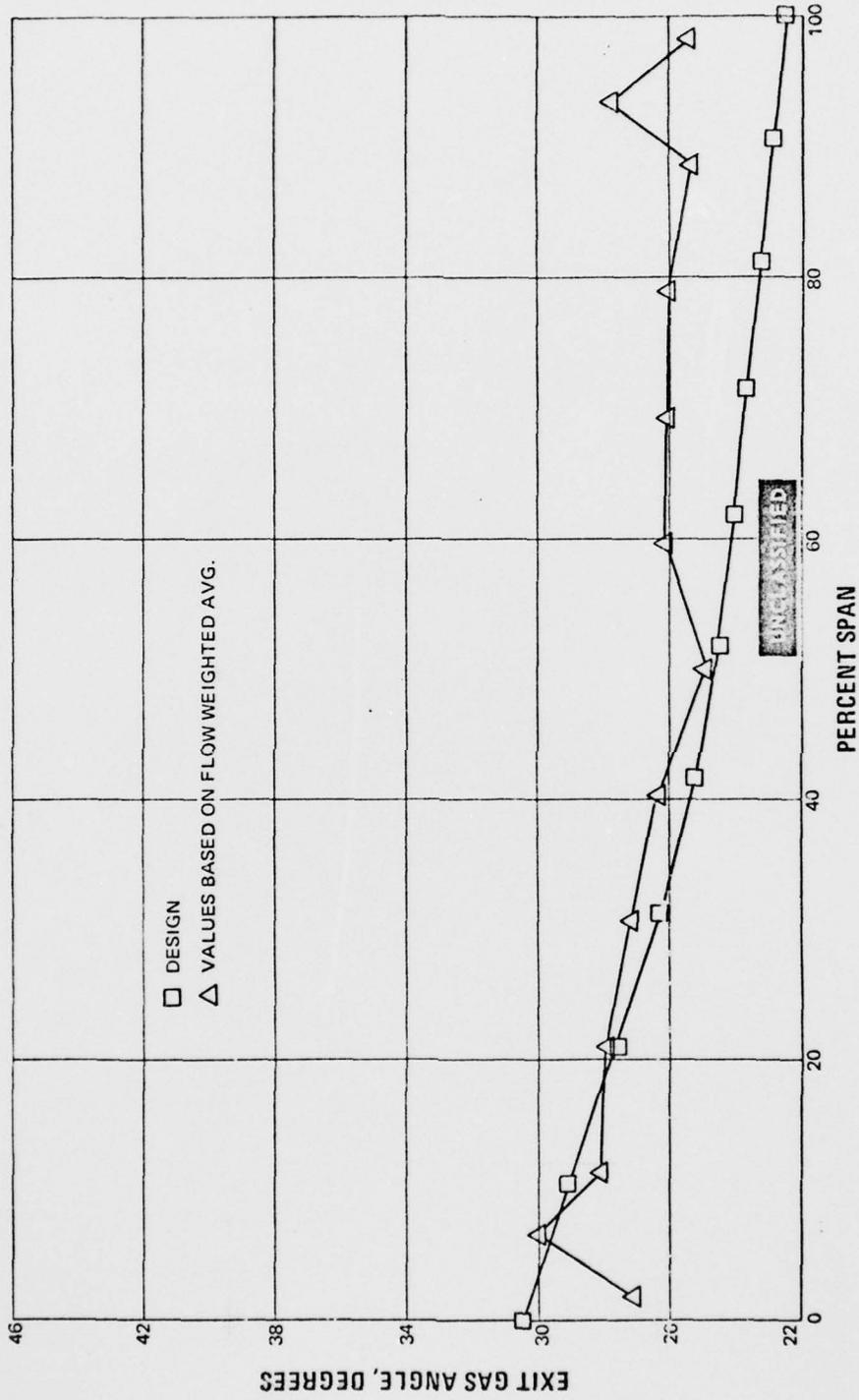


Figure 59 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Removed, Mid-span Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

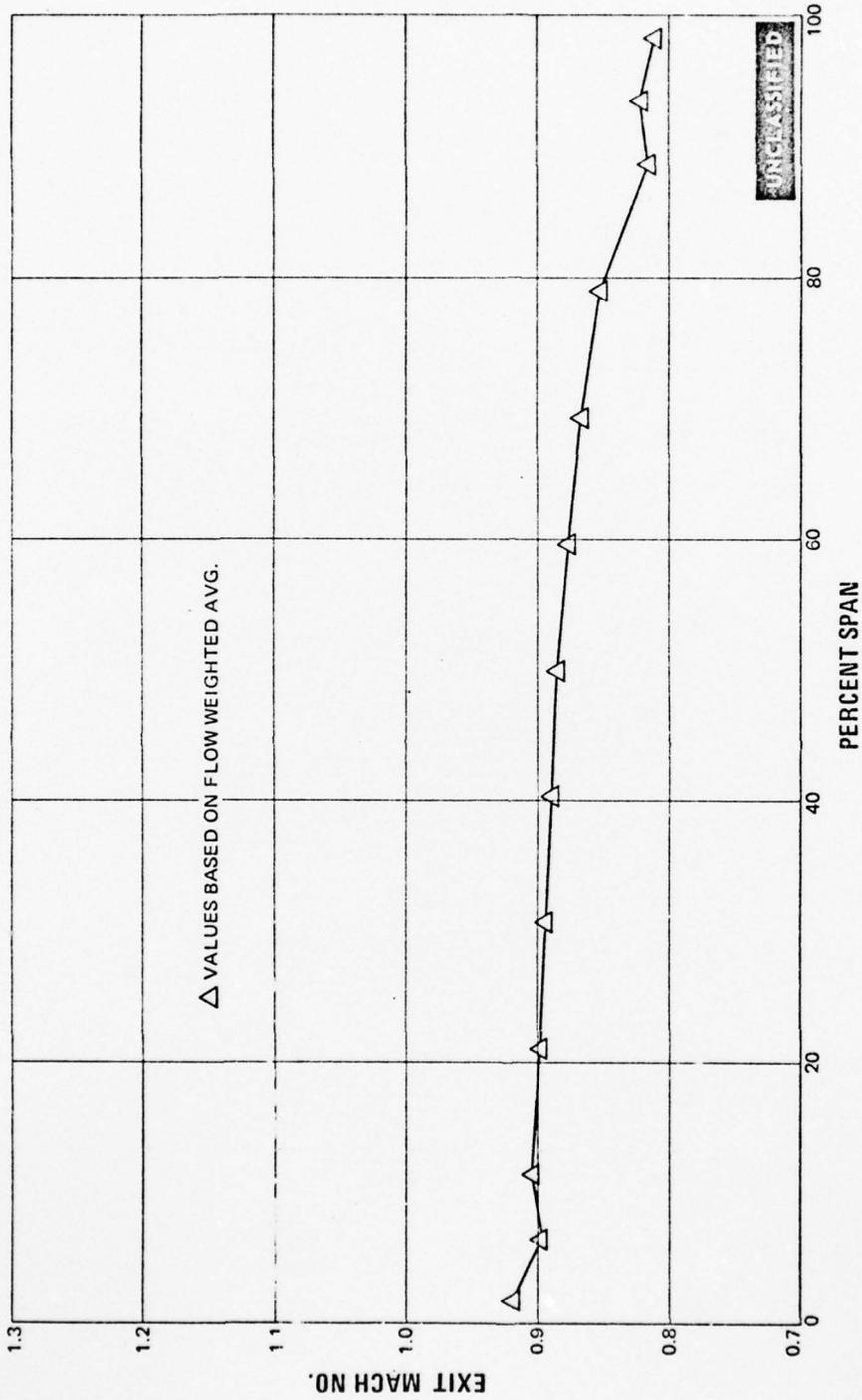


Figure 60 Spanwise Exit Mach Number Distribution, Second Vane - Screen Removed, Midspan Exit Mach No. = 0.885, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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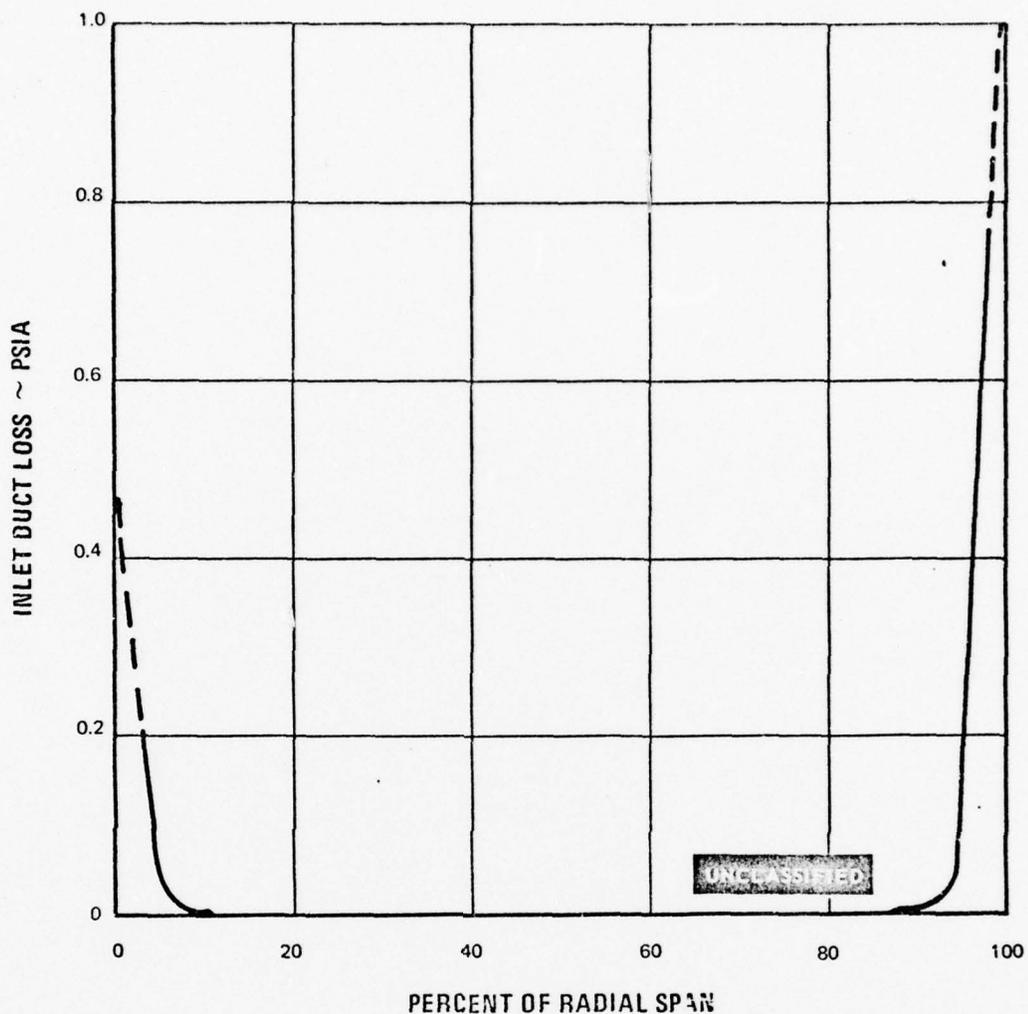


Figure 61 Inlet Duct Loss Versus Percent Radial Span—Second Vane Cascade With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

(U) An inlet screen was then installed in the cascade in order to restore a more realistic turbulence intensity level. The performance data of the baseline airfoil with the screen and optimum boundary layer bleeds are shown in Figures 62 through 67. It is important to note that the loss level (0.0326) duplicated the initial baseline value (0.034) within experimental accuracy ( $\pm 0.003$ ). Oil and graphite flow visualization tests on these airfoils shown in Figures 68 and 69, indicated uniform, unseparated flow. Based on these results, the recontoured airfoil, contoured end-wall and recambered airfoil cascade packs were tested with the screen in the inlet. After these tests, the baseline evaluation was repeated in order to verify the integrity of these tests. The performance data of the repeated tests are shown in Figures 70 through 75. The airfoil surface static pressures are shown in Figures 76 through 78, and the flow visualization photographs in Figures 79 and 80. The repeated baseline tests (overall loss coefficient of 0.0349) verified the previous baseline (overall loss coefficient of 0.0326) very closely.

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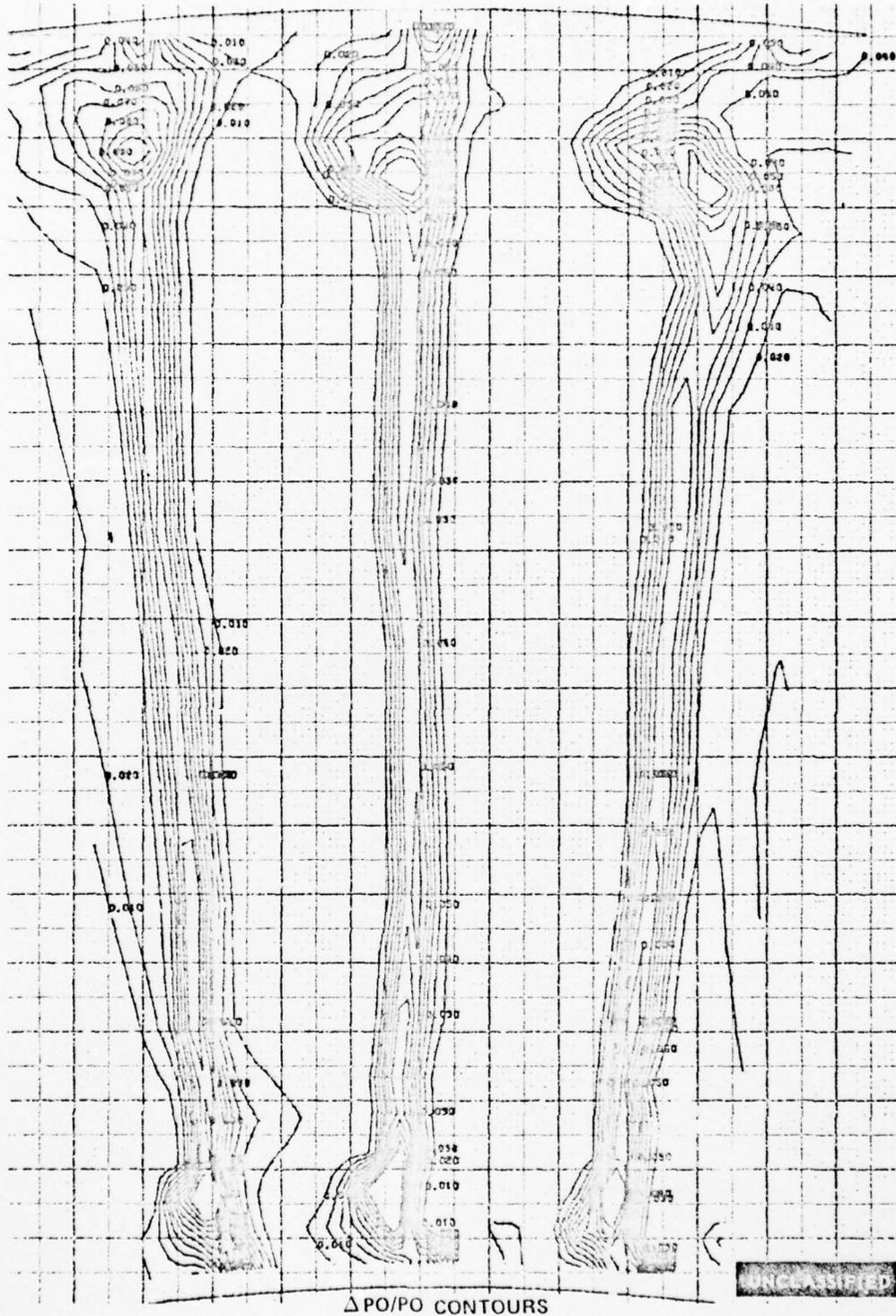


Figure 62 Pressure Loss Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

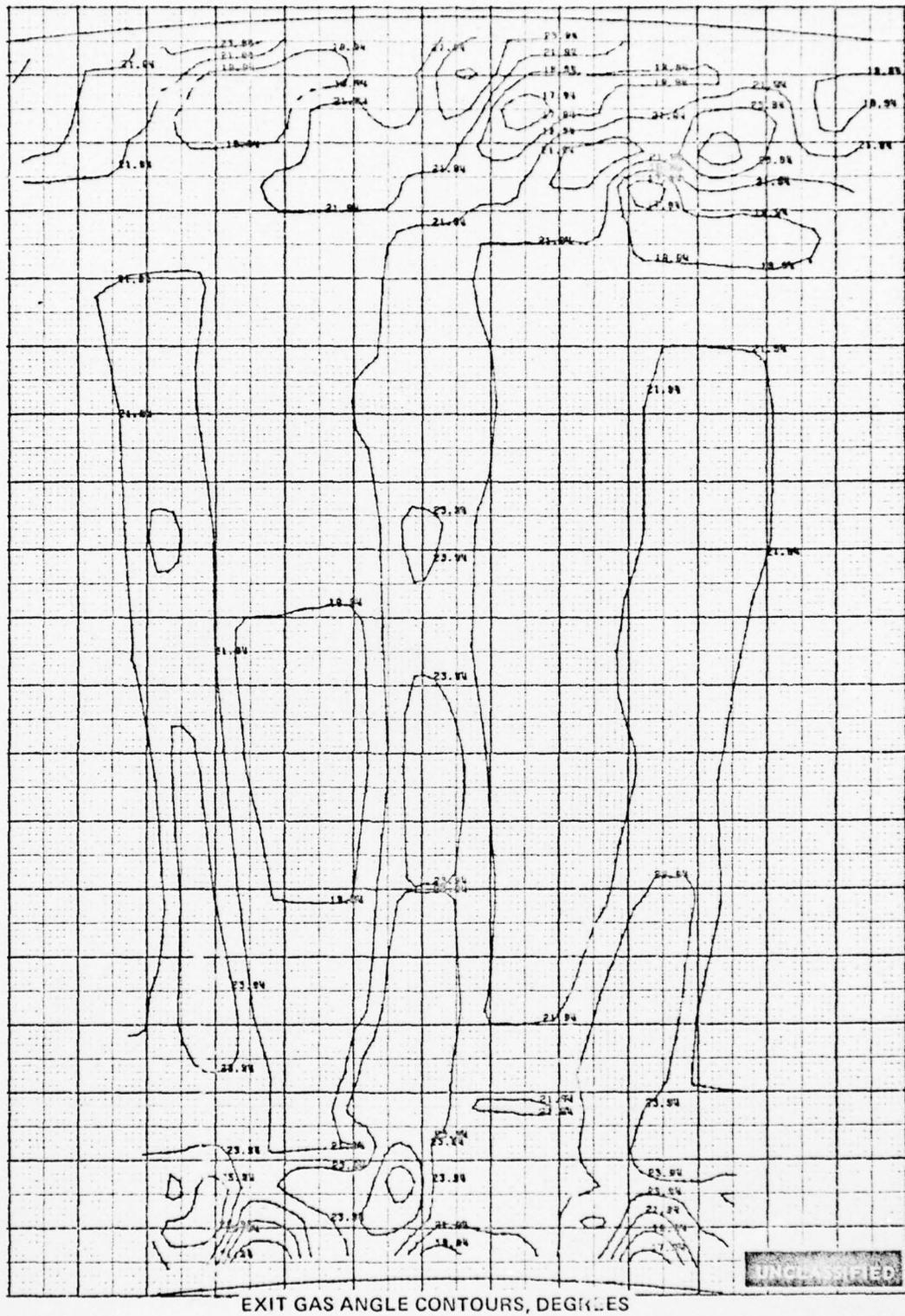


Figure 63 Exit Gas Angle Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

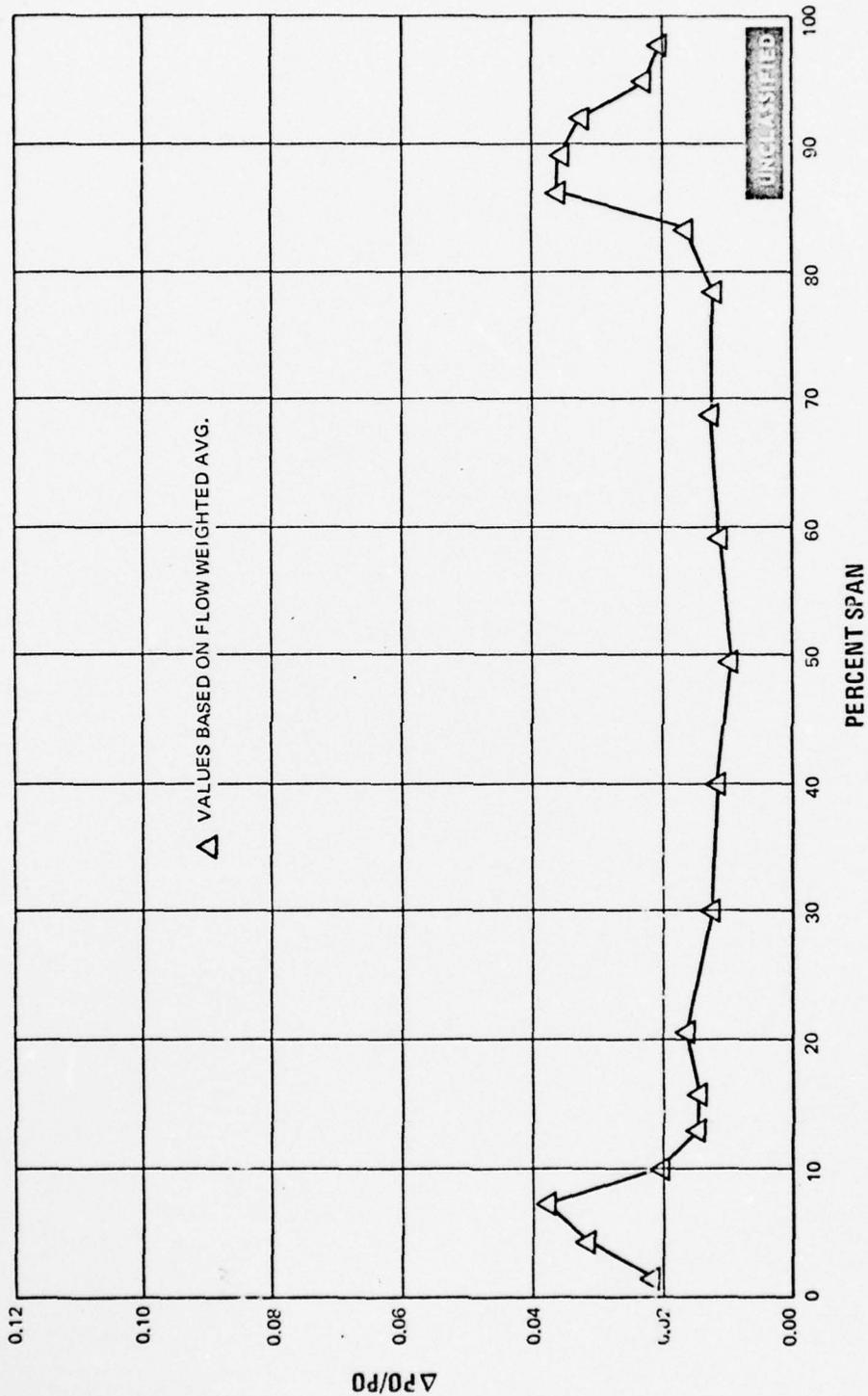


Figure 64 Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and  
Optimum Boundary Layer Bleeds

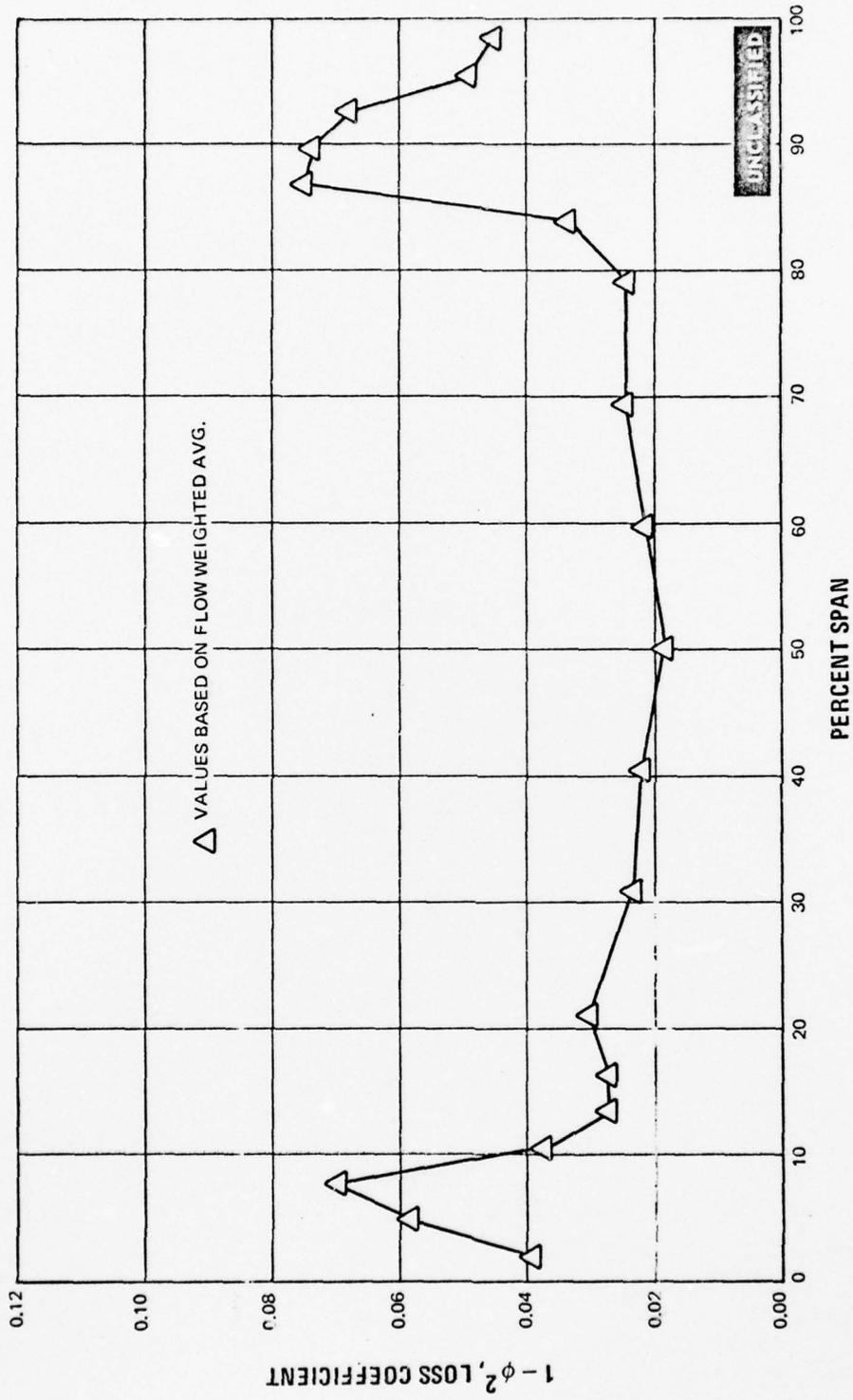


Figure 65 Spanwise Loss Coefficient Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

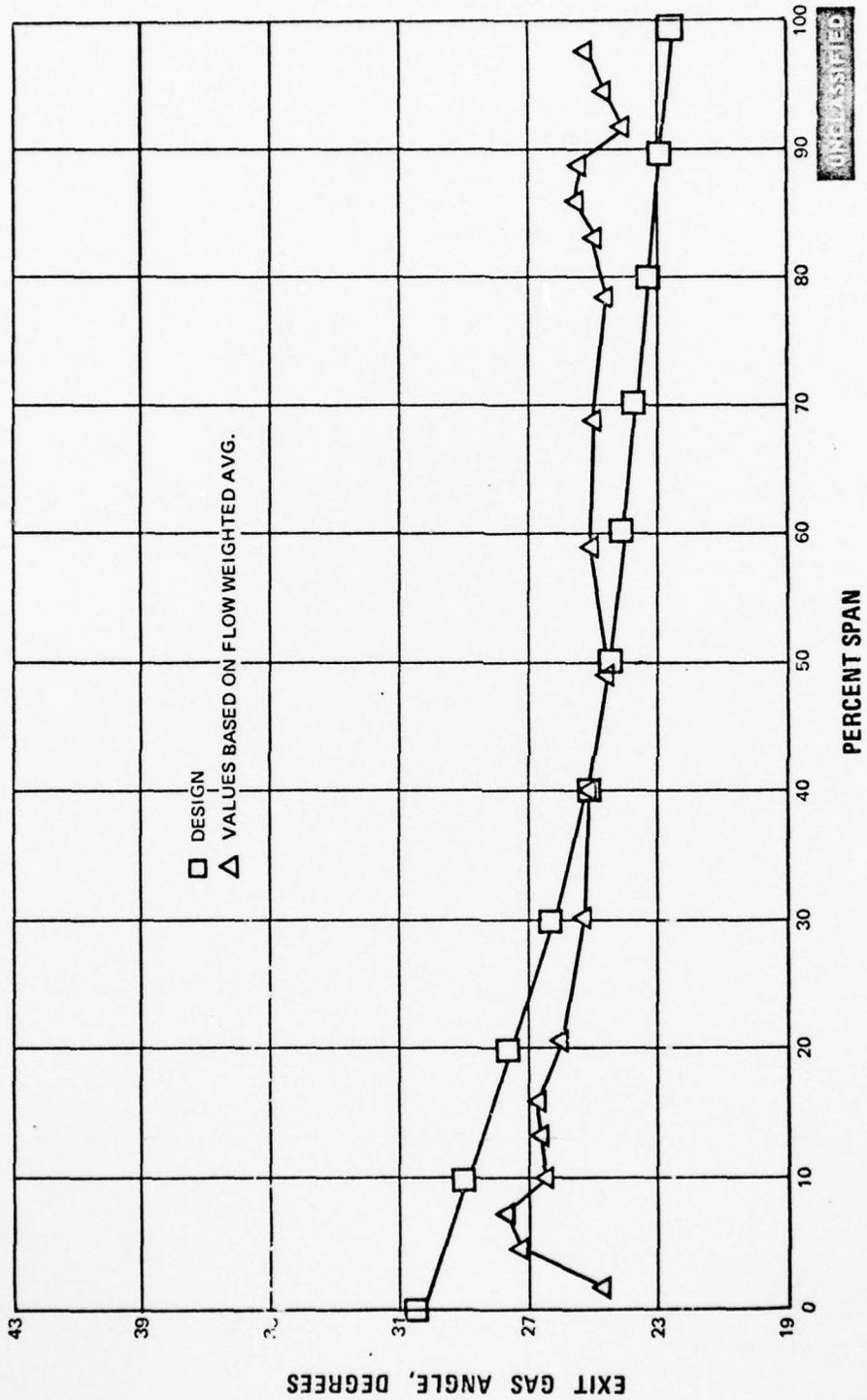


Figure 66 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and  
Optimum Boundary Layer Bleeds

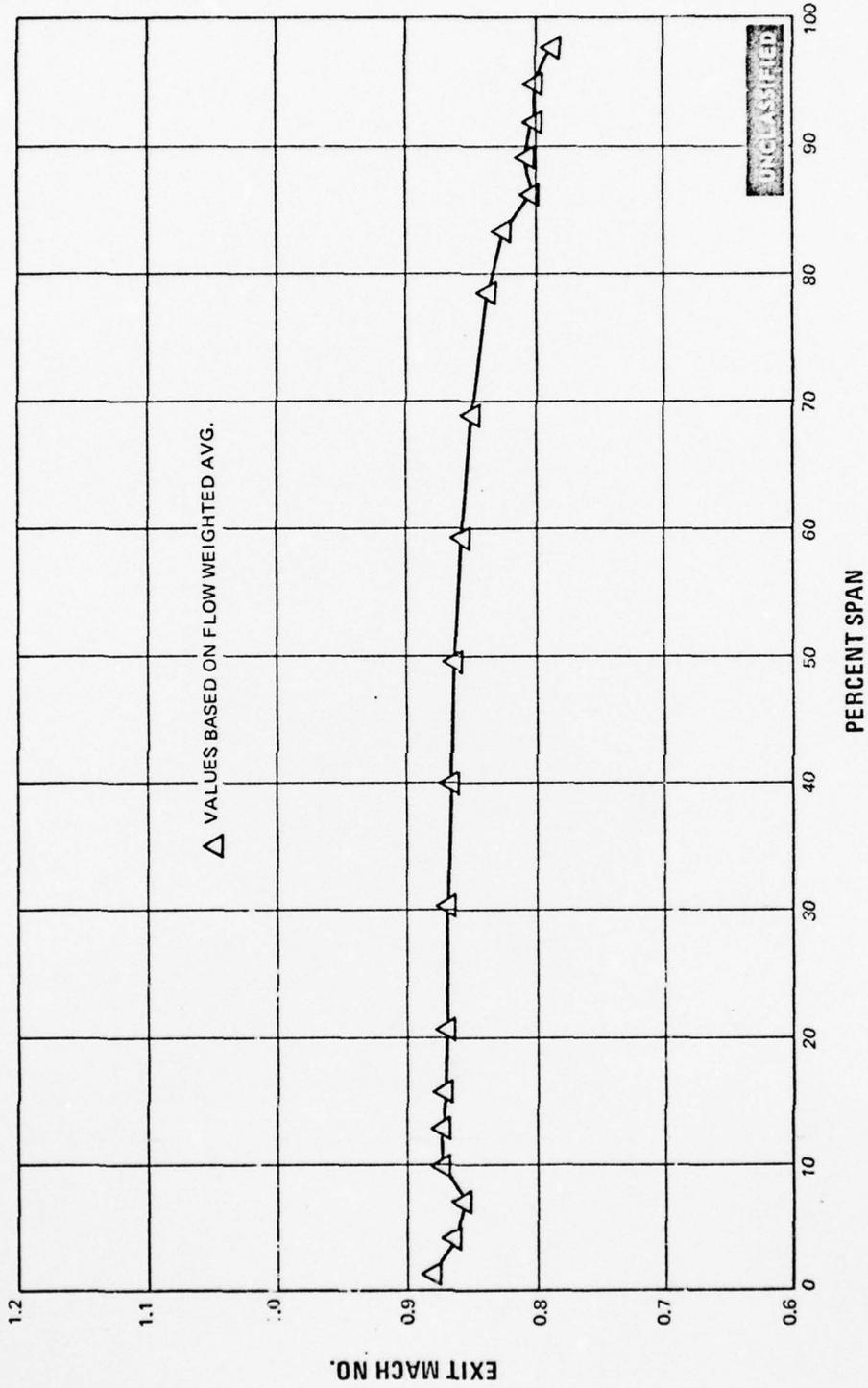


Figure 67 Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.862, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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Figure 68 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; View of Downstream Inside Diameter; Midspan Exit Mach No. =0.862



Figure 69 Oil and Graphite Flow Patterns—Second Vane with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; View of Downstream Outside Diameter; Midspan Exit Mach No. =0.862

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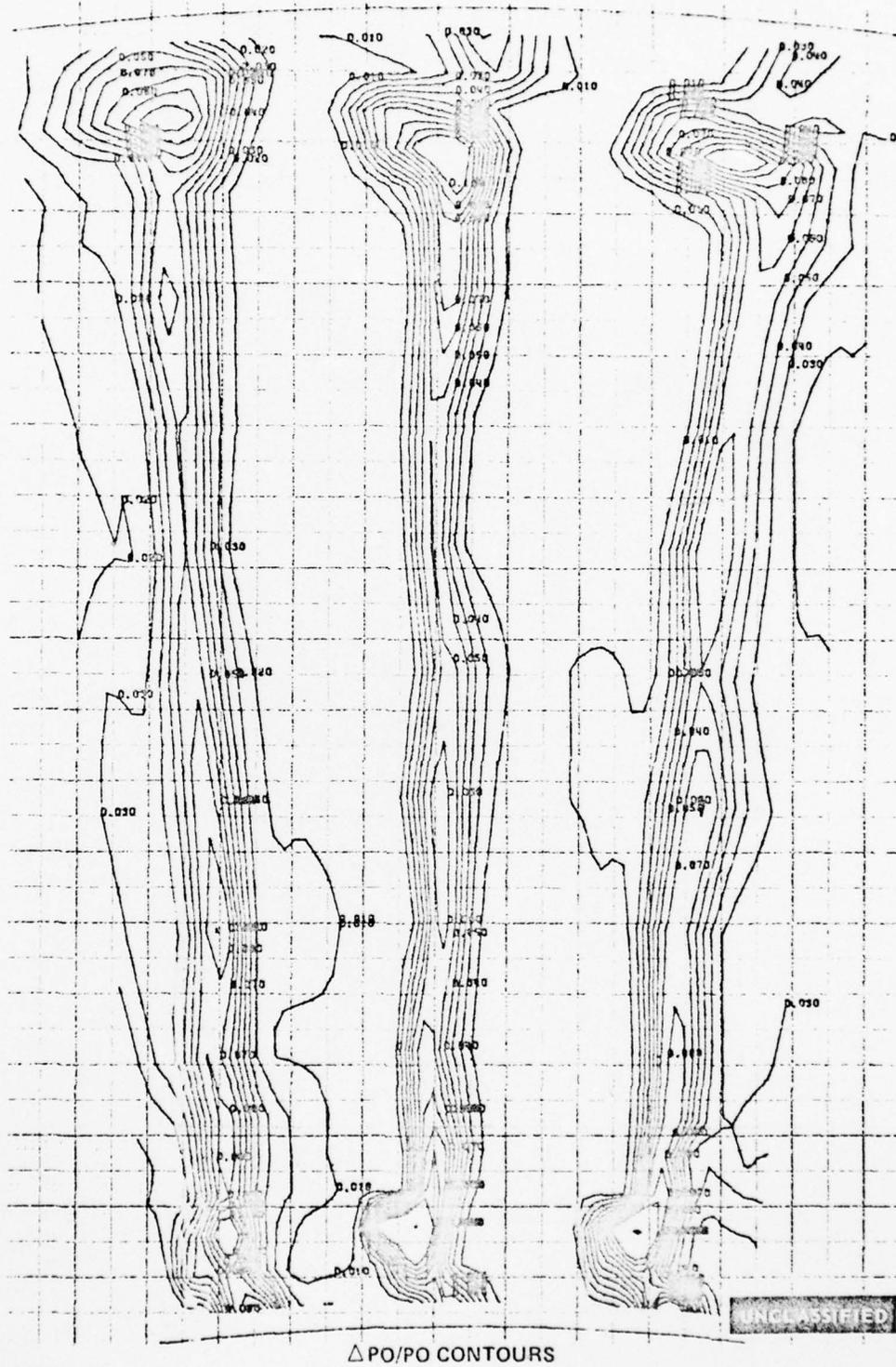


Figure 70 Pressure Loss Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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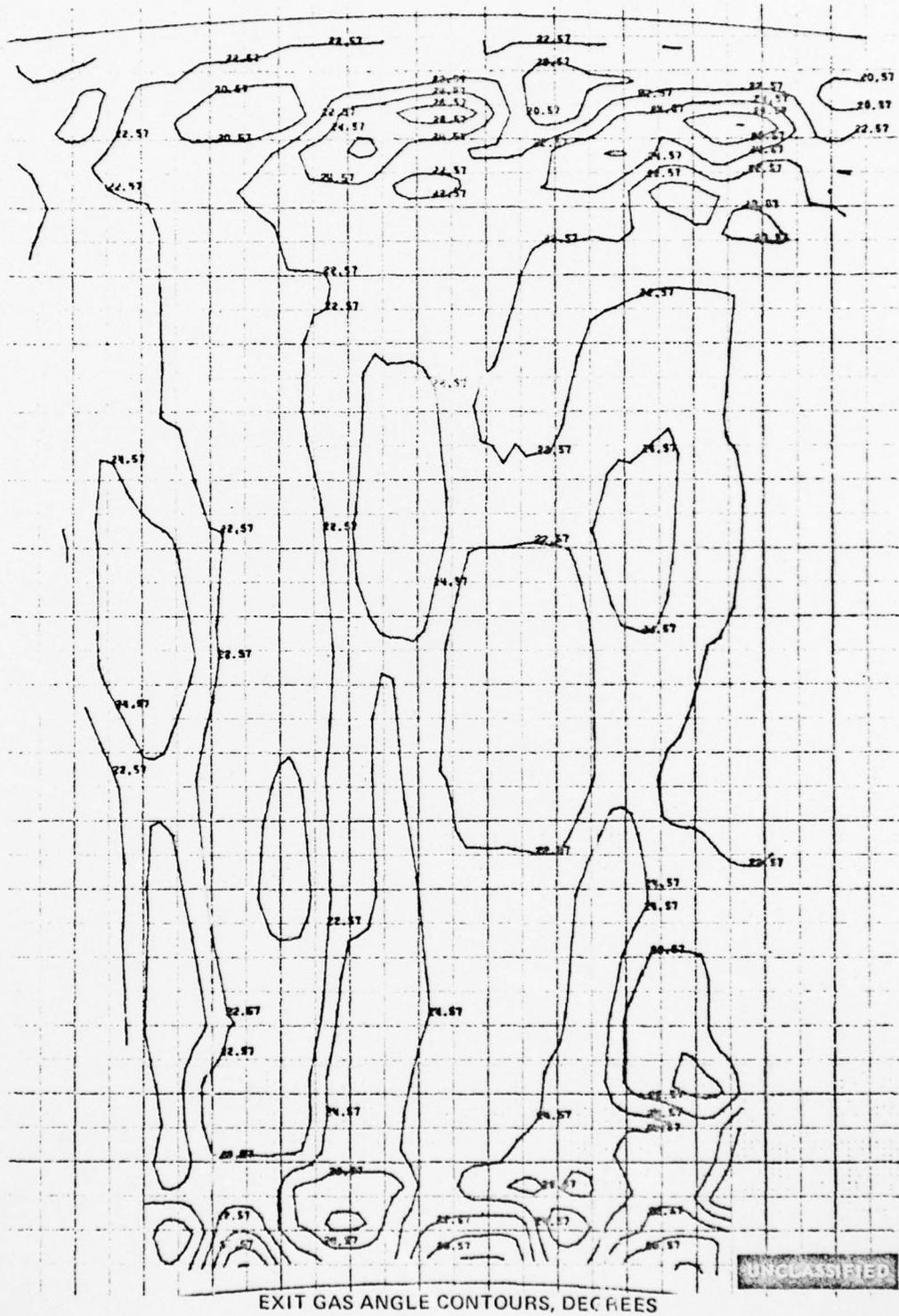


Figure 71 Exit Gas Angle Contours, Second Vane - Screen, Installed, Three Flow Passages, Midspan Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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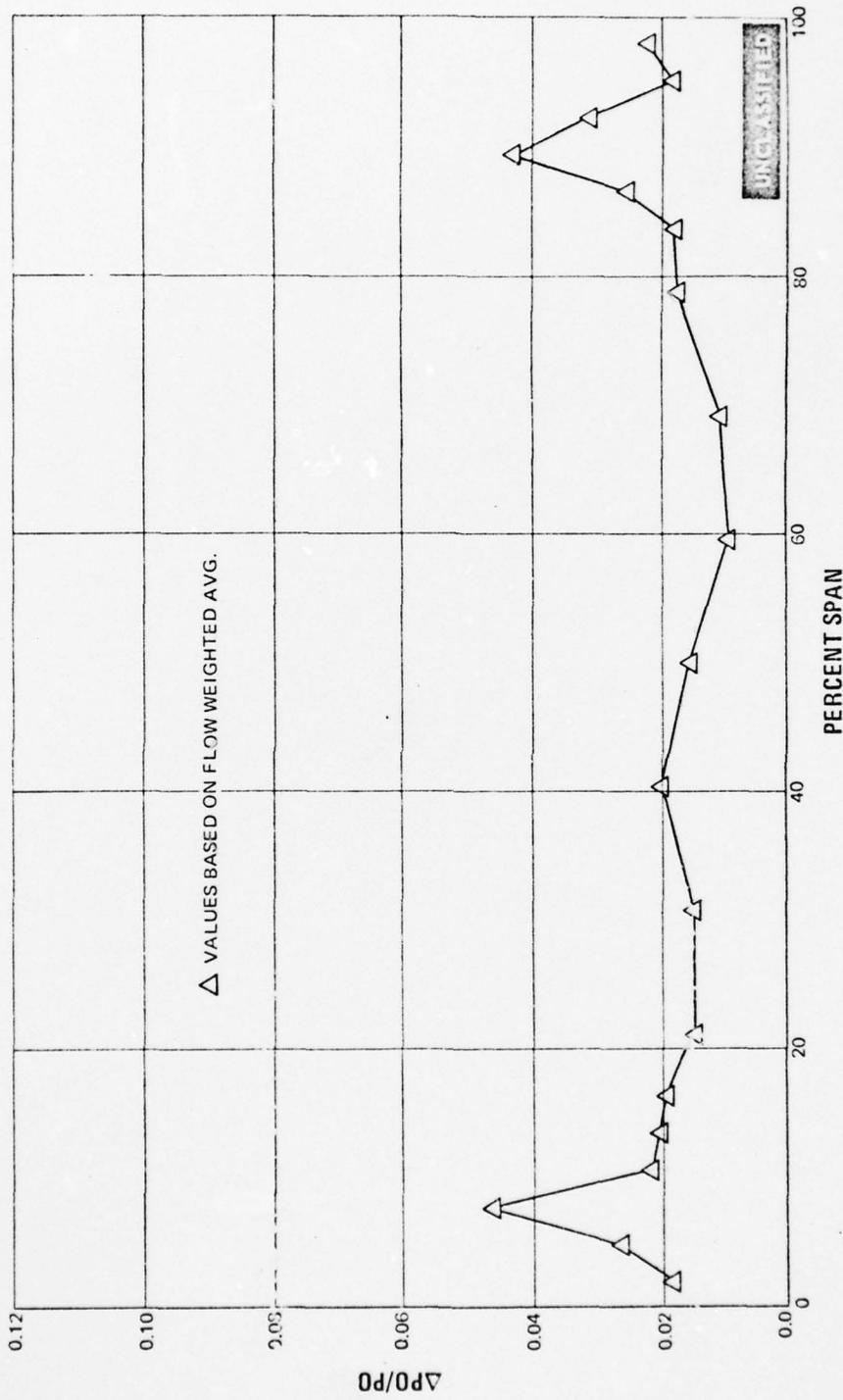


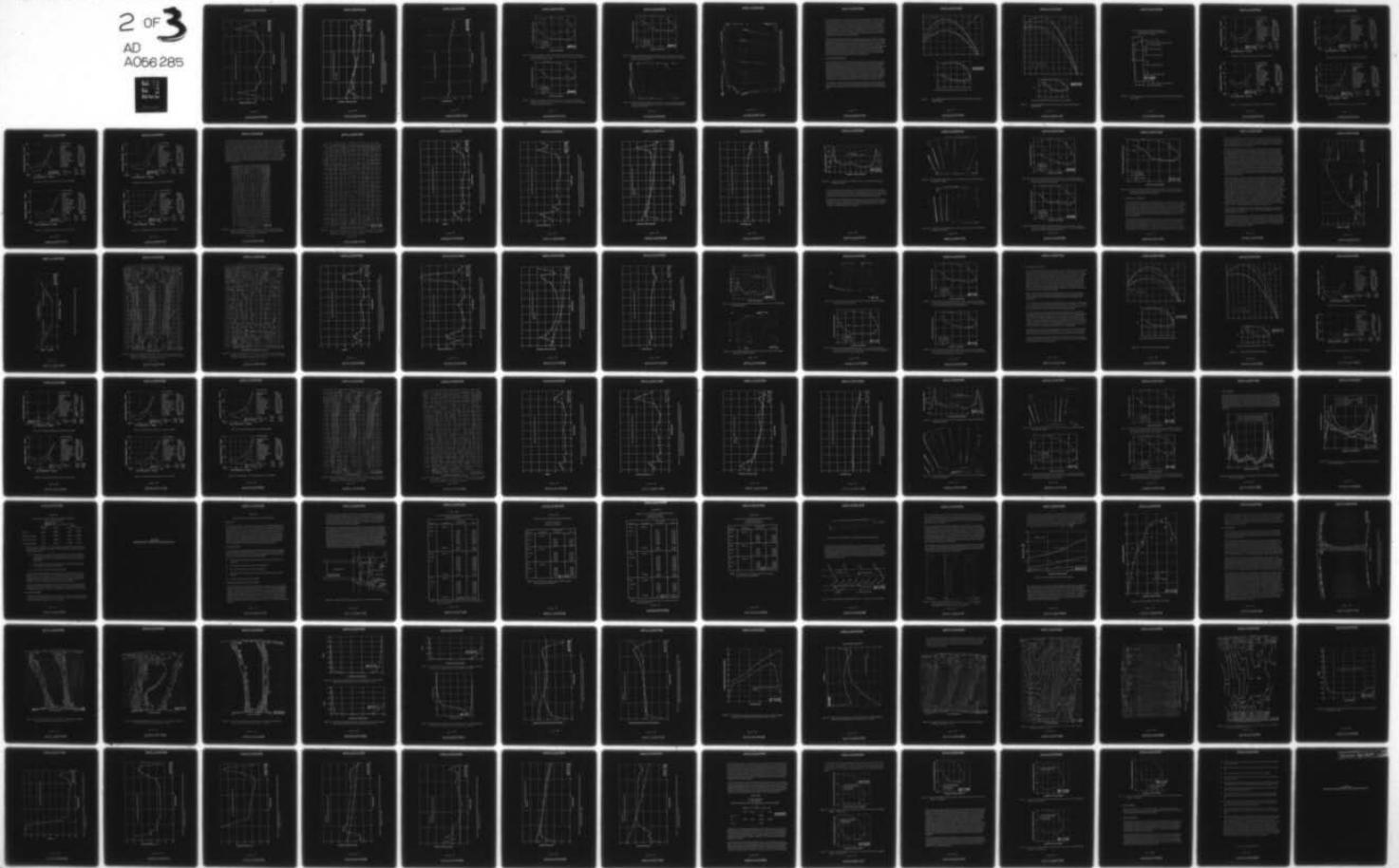
Figure 72 Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and  
Optimum Boundary Layer Bleeds

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PRATT AND WHITNEY AIRCRAFT GROUP EAST HARTFORD CONN F/G 21/5  
INVESTIGATION OF A HIGHLY LOADED TWO-STAGE FAN-DRIVE TURBINE. V--ETC(U)  
DEC 69 H WELNA, D E DAHLBERG, W H HEISER F33615-68-C-1208  
PWA-3827 AFAPL-TR-69-92-VOL-4 NL

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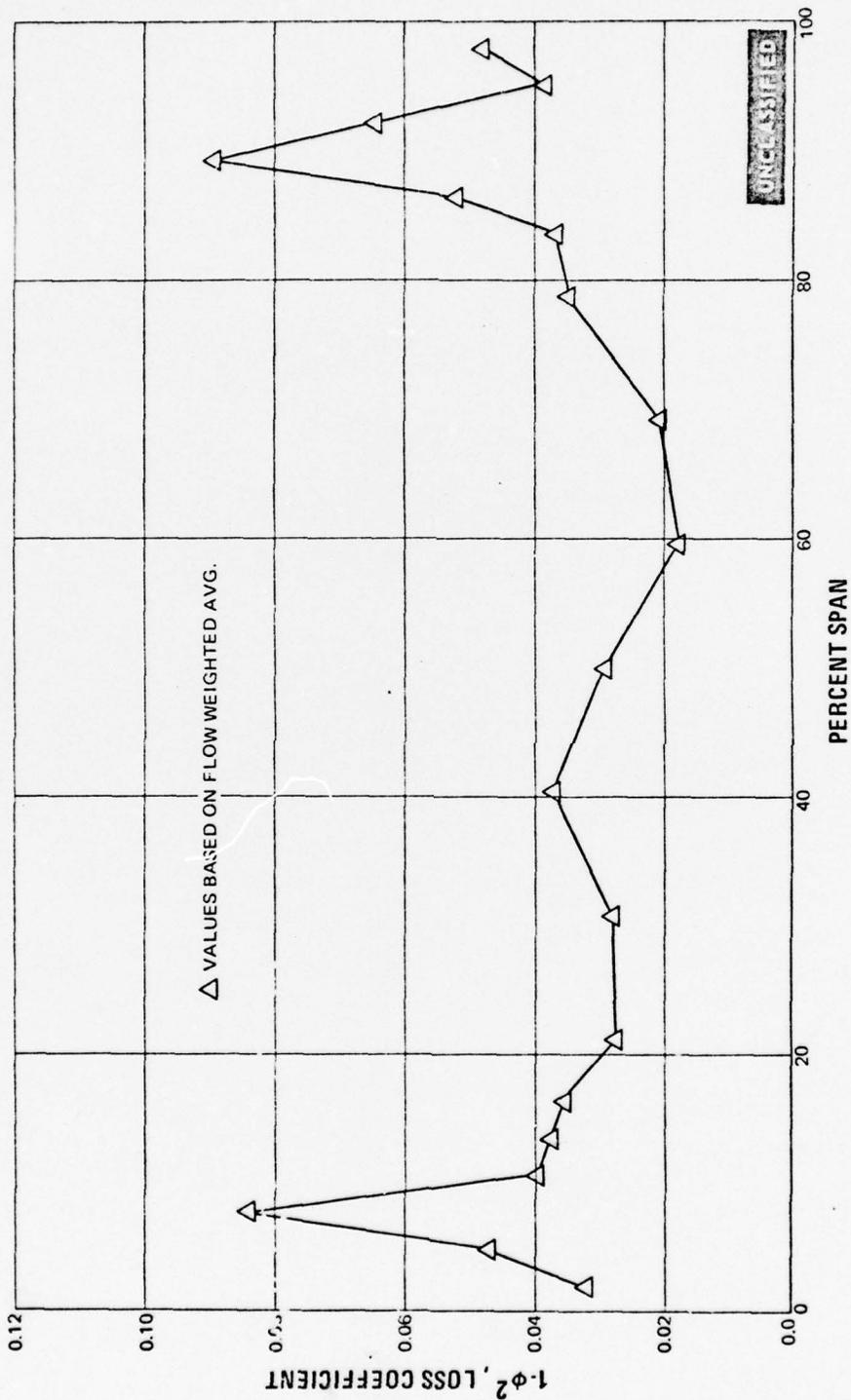


Figure 73 Spanwise Loss Coefficient Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

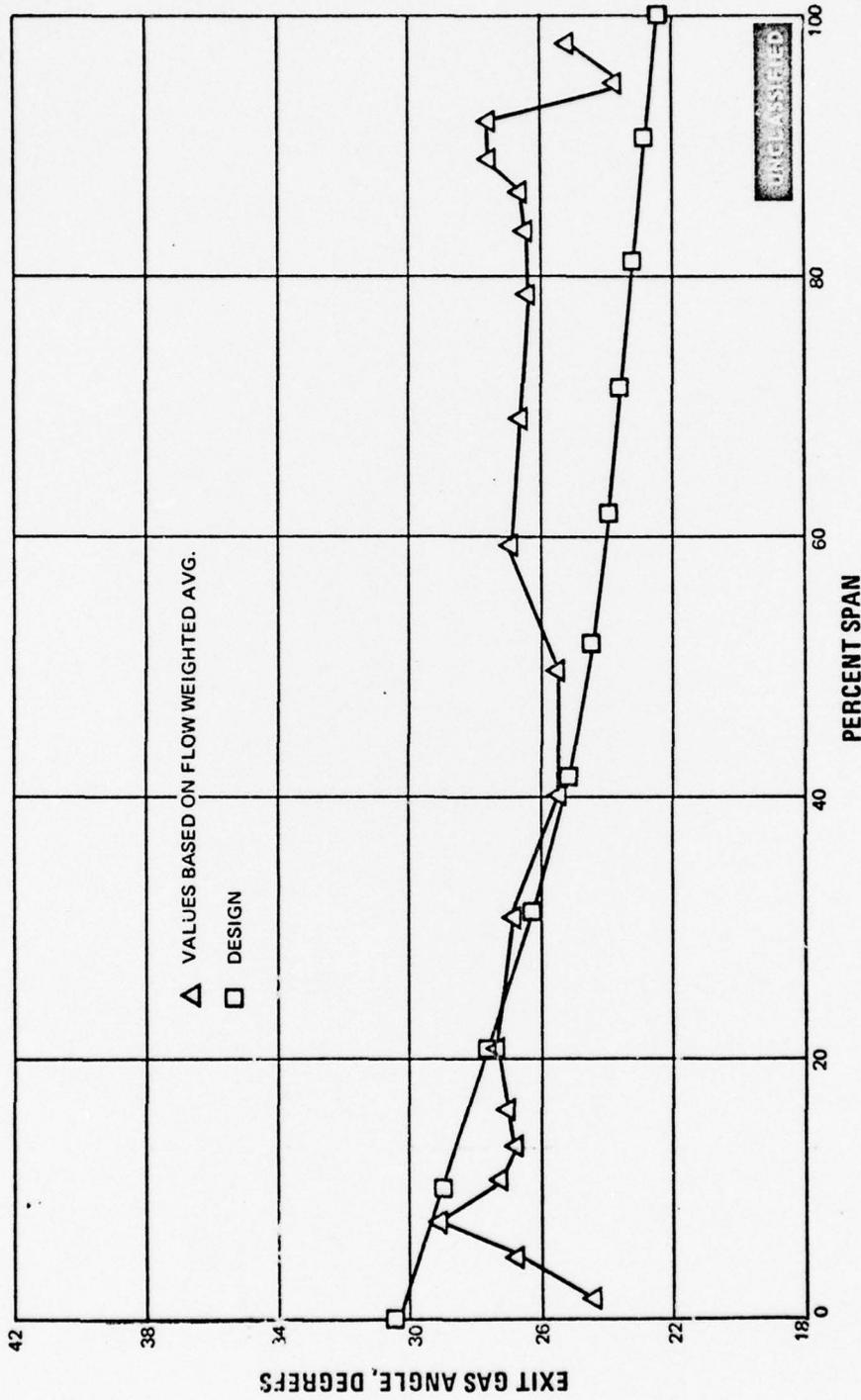


Figure 74 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and  
Optimum Boundary Layer Bleeds

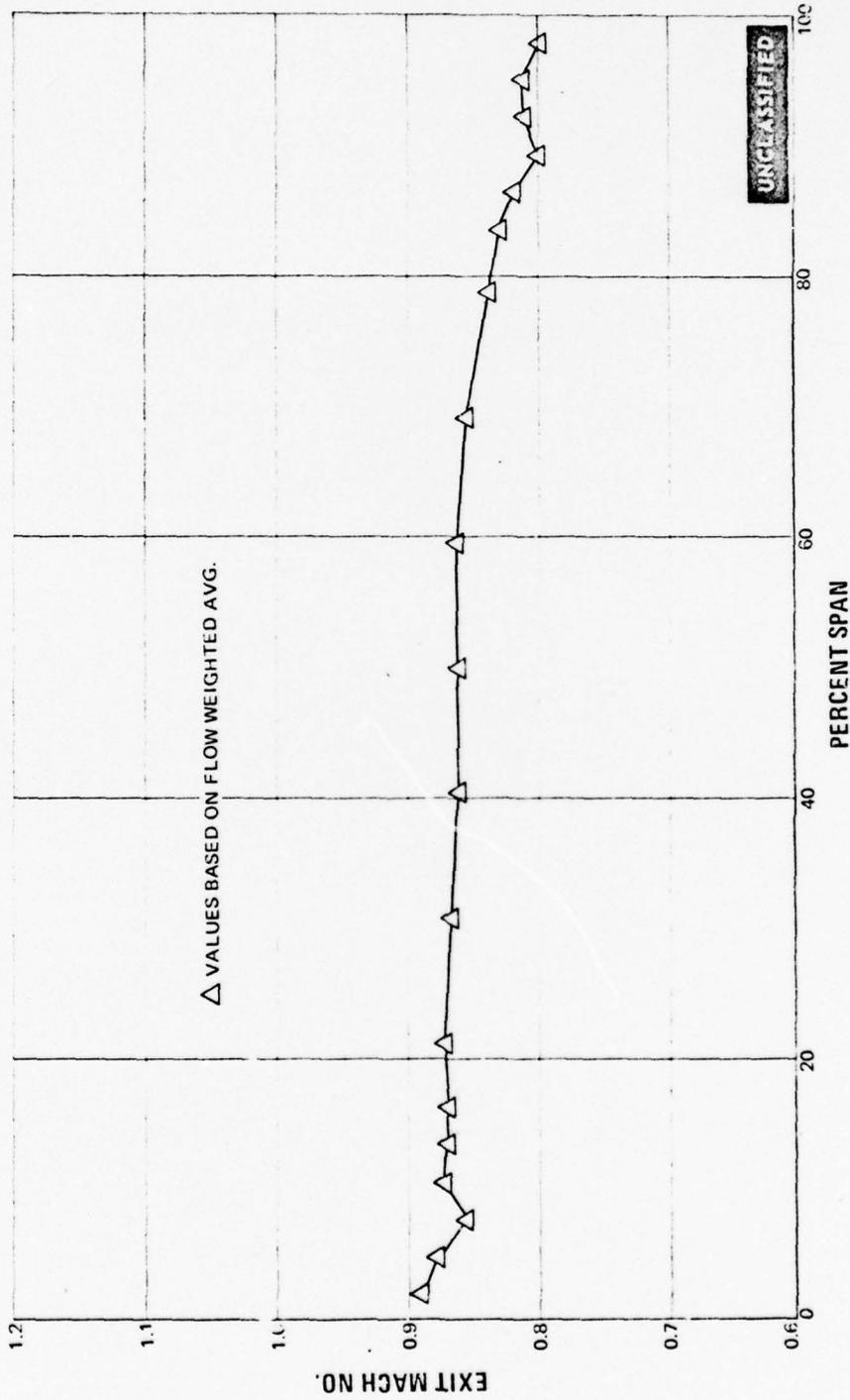


Figure 75 Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.860, Baseline With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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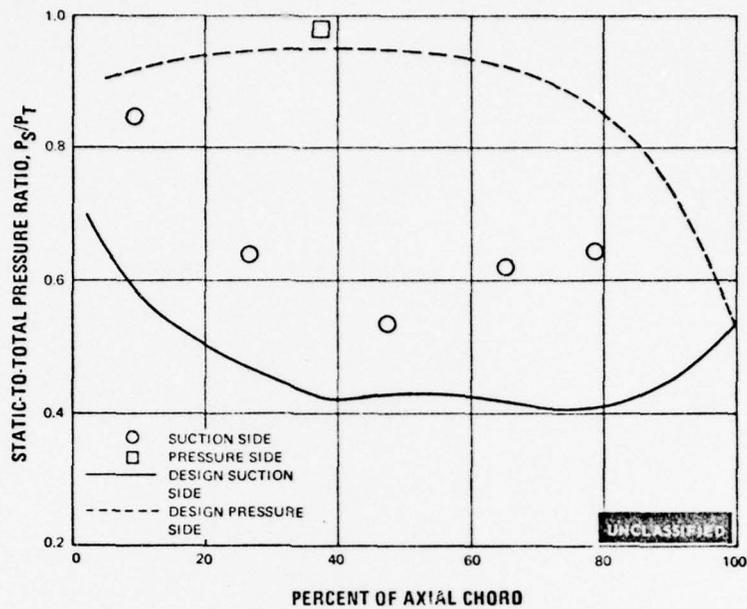


Figure 76 Static-to-Total Pressure Ratio Versus Percent of Axial Chord. Second Vane Baseline With Redesigned Inlet Guide Vanes. Optimum Boundary Layer Bleeds and Inlet Screen—Root Section

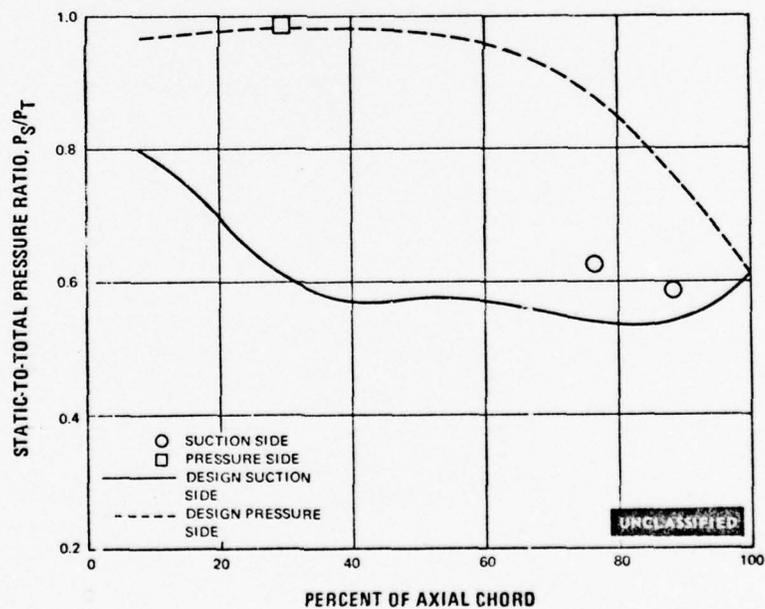


Figure 77 Static-to-Total Pressure Ratio Versus Percent of Axial Chord. Second Vane Baseline With Redesigned Inlet Guide Vanes. Optimum Boundary Layer Bleeds and Inlet Screen—Mean Section

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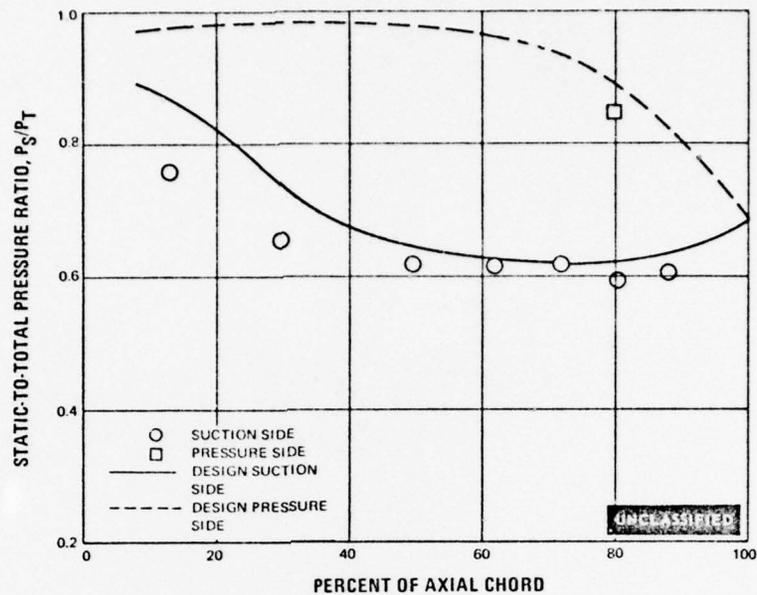


Figure 78 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Baseline With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section



Figure 79 Oil and Graphite Flow Patterns—Second Vane Baseline with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; Midspan Exit Mach No. = 0.860

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Figure 80 Oil and Graphite Flow Patterns--Second Vane Baseline with Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen Installed; Midspan Exit Mach No. = 0.860

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(U) Turbine airfoils are, as we know, very sensitive to the location of boundary layer transition, which in turn is strongly affected by the inlet conditions. A good example is seen by the bump at the midspan airfoil loss coefficient in all the data, regardless of the end-wall treatment. The combination of the type of inlet guide vane, inlet duct geometry and inlet turbulence triggered the transition earlier in the middle of the airfoil than anywhere else, causing losses to be slightly higher there. However, since this feature consistently reappeared in all the remaining data, and since even the highest midspan loss coefficient level was comparable to the design value for the second vane, no further note was taken of this flow behavior.

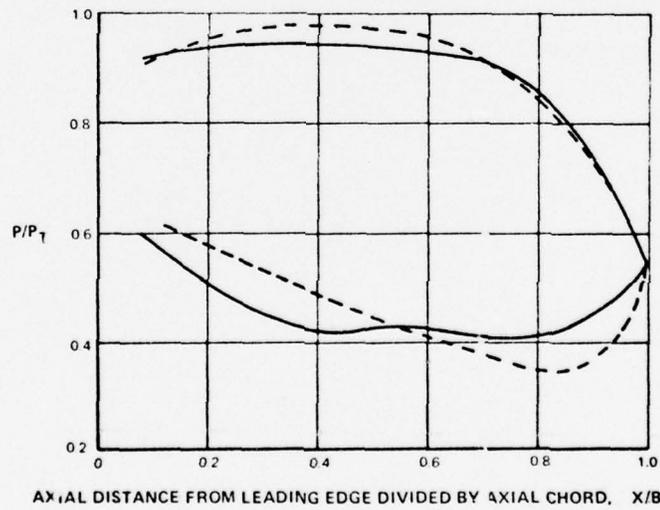
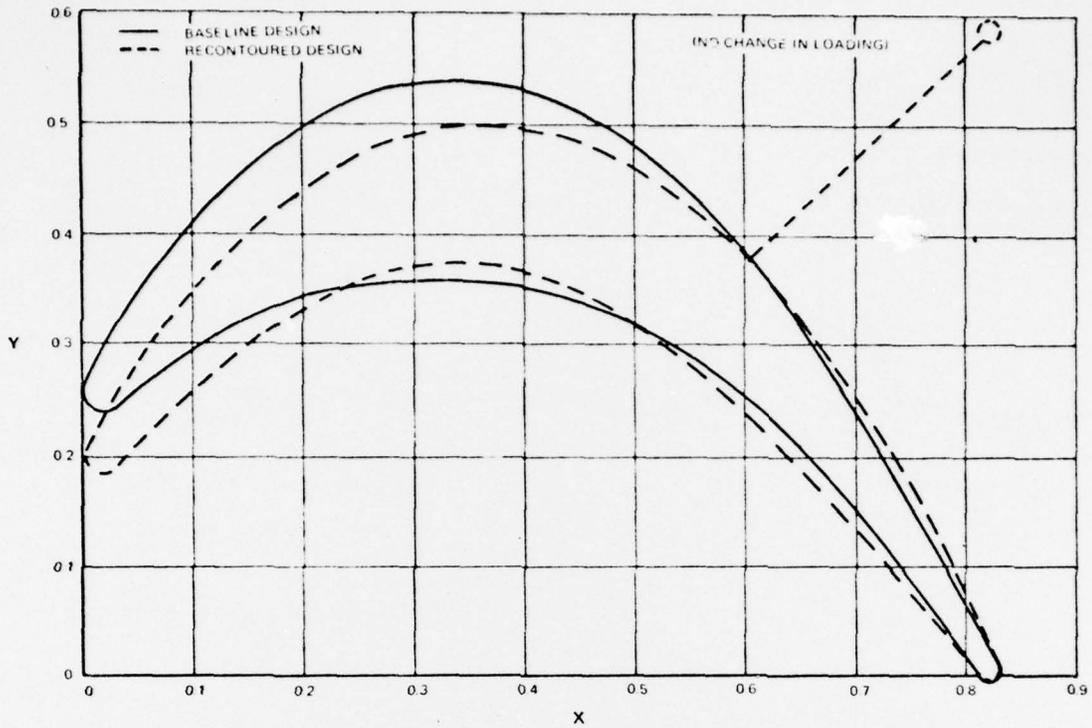
(U) Even though the remainder of this program concentrates on end losses rather than profile losses, it was felt that the most reliable data would be obtained from the closest simulation of turbine conditions in an engine. Therefore, all of our experience indicates that these actual conditions were met with the redesigned inlet guide vane which set the proper test airfoil conditions, the optimized boundary layer bleeds which minimized the effect of the inlet boundary layer effects, and the inlet screen which maintains engine-type turbulence intensity. Therefore, the effects of airfoil recontouring, end-wall recontouring and airfoil recambering were investigated with the redesigned inlet guide vane, optimum boundary layer bleed and an inlet screen.

## 6. RECONTOURED AIRFOILS

(U) One method of reducing the end wall losses that was investigated was local recontouring of the baseline second vane airfoil. The airfoil surface static pressure gradient over the leading portion was reduced in order to decrease the loading at the airfoil leading edge, while keeping the overall loading constant. A comparison of the baseline root and tip airfoil profiles with the recontoured profiles, along with the predicted airfoil surface static pressure distributions is shown in Figures 81 and 82. These root and tip recontoured sections were faired into the existing midspan contour at approximately the 25 and 75 percent span locations. These changes are intended to delay the onset of strong secondary flow in the upstream portion of the channel and thereby, to reduce the total accumulation of losses near the airfoil suction surface corners.

(U) The elevation of the recontoured second vane is shown in Figure 83, and the profiles of the airfoil section are presented in Figures 84 through 91. The fabrication coordinates for each airfoil profile are tabulated in Tables XIII through XX of the Appendix.

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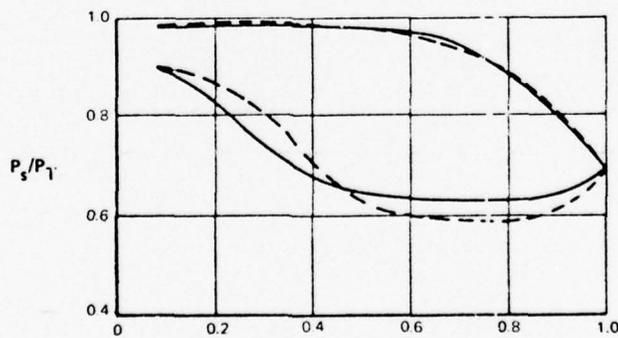
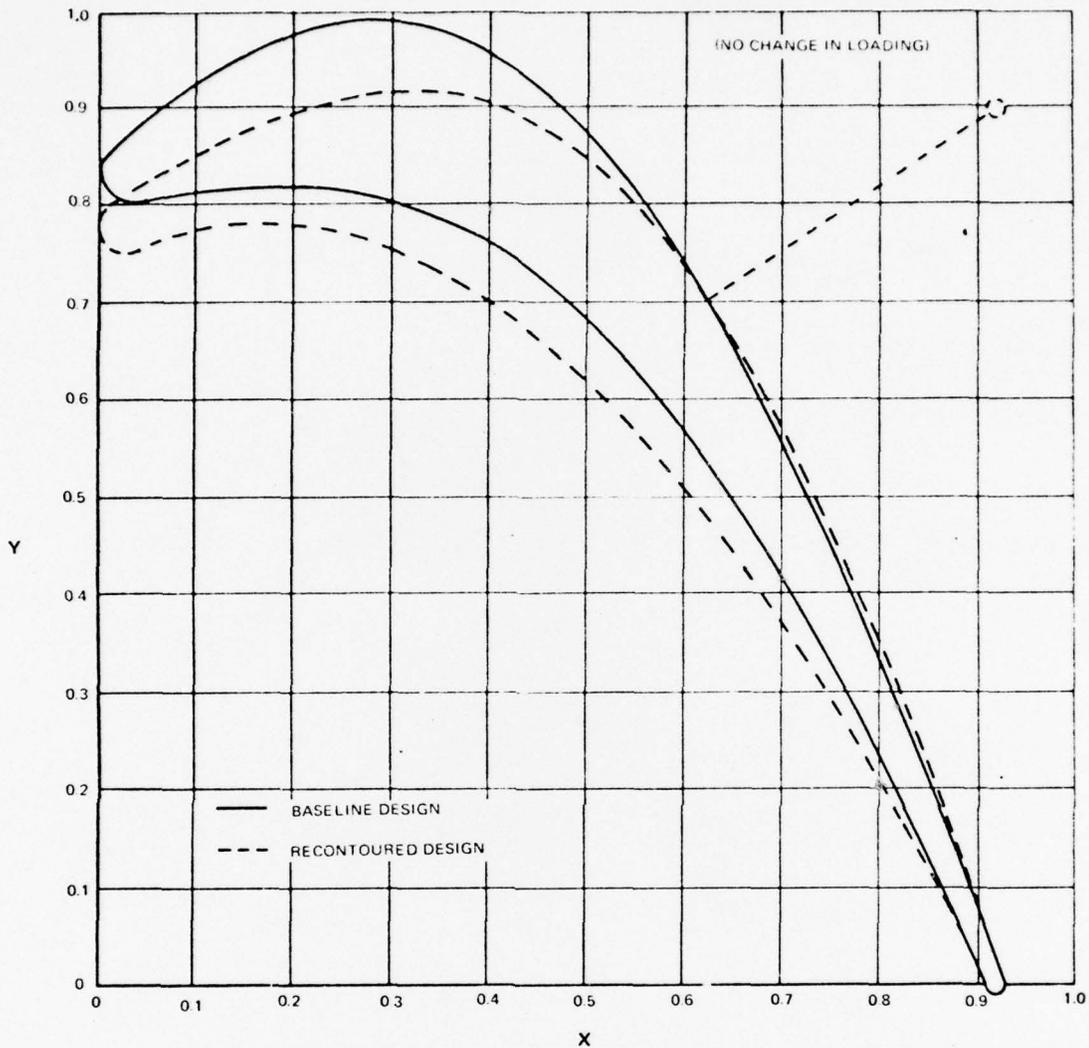


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Figure 81 Second Vane Baseline Airfoil Recontouring Root Section Static Pressure Redistribution

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AXIAL DISTANCE FROM LEADING EDGE DIVIDED BY AXIAL CHORD, X/B

Figure 82 Second Vane Baseline Airfoil Recontouring, Tip Section Static Pressure Redistribution

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NOTE: ACTUAL AIRFOIL SHOULD BE EXTENDED BY  
CONTINUATION OF FAIRING OF GIVEN SECTIONS  
TO R=11.945 and R=7.0 INCHES

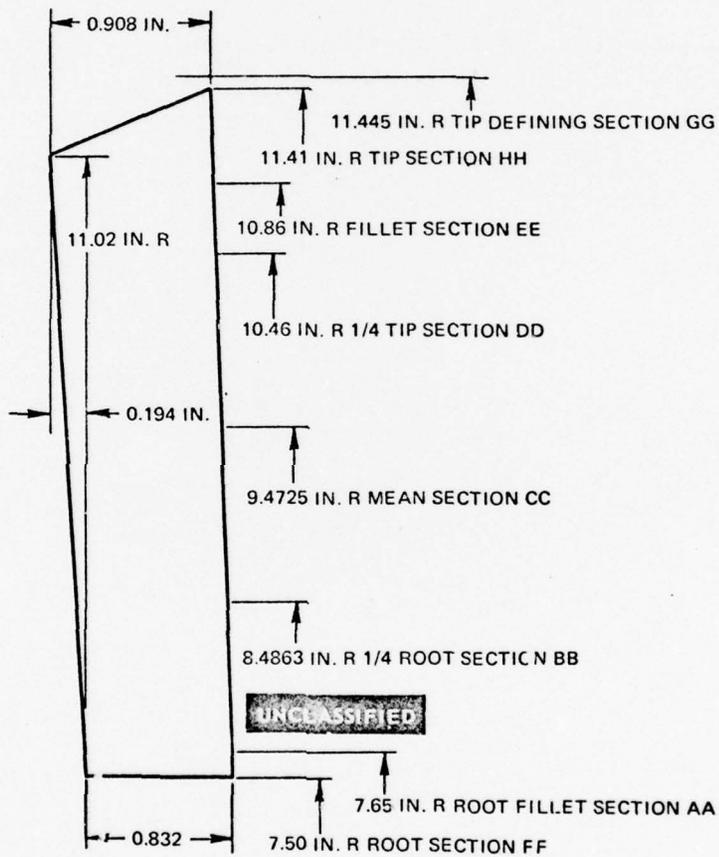


Figure 83 Elevation and Section Location of the Recambered and Recontoured Second Vane Airfoils

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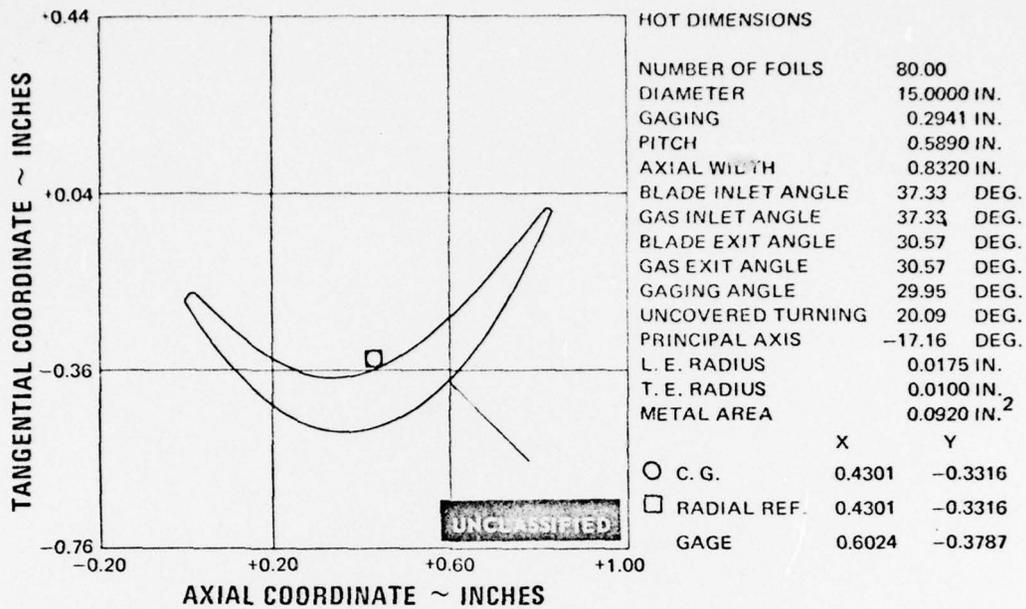


Figure 84 Recontoured Second Vane, Root Section (FF)

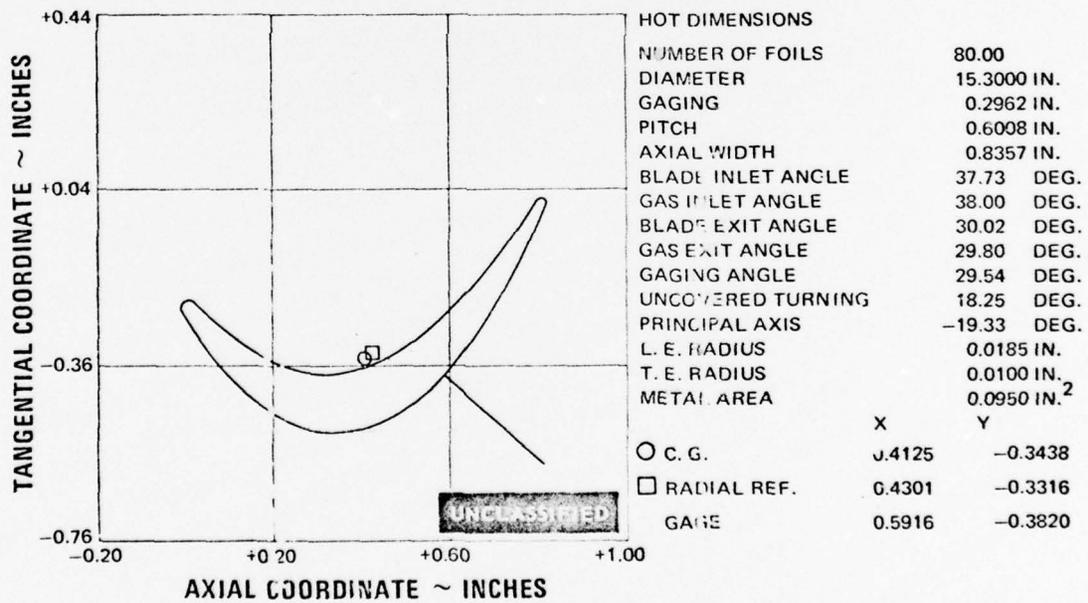


Figure 85 Recontoured Second Vane, Root Fillet Section (AA)

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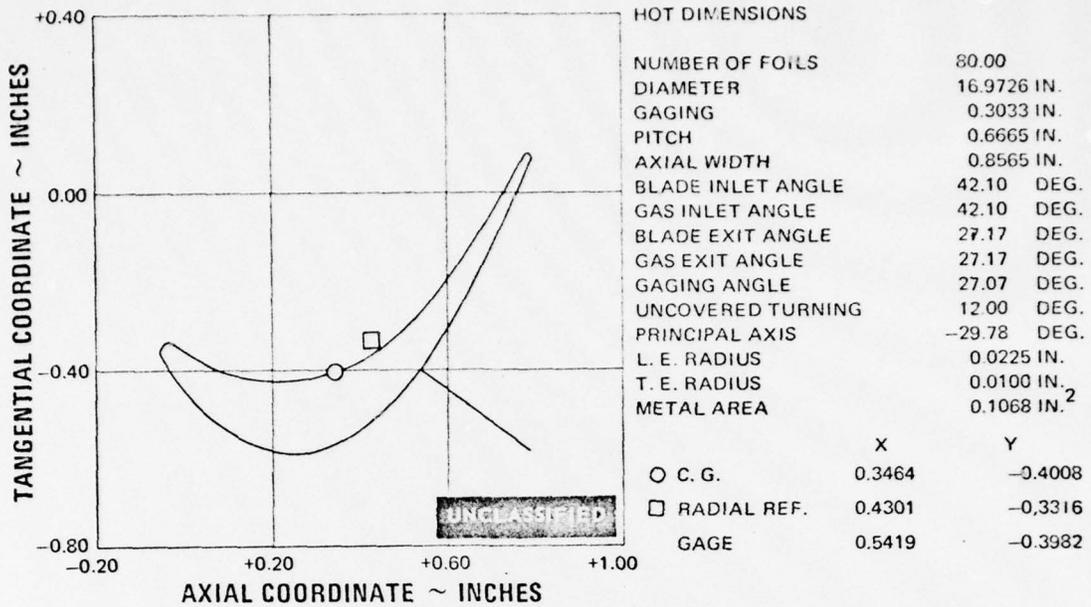


Figure 86 Recontoured Second Vane, 1/4 Root Section (BB)

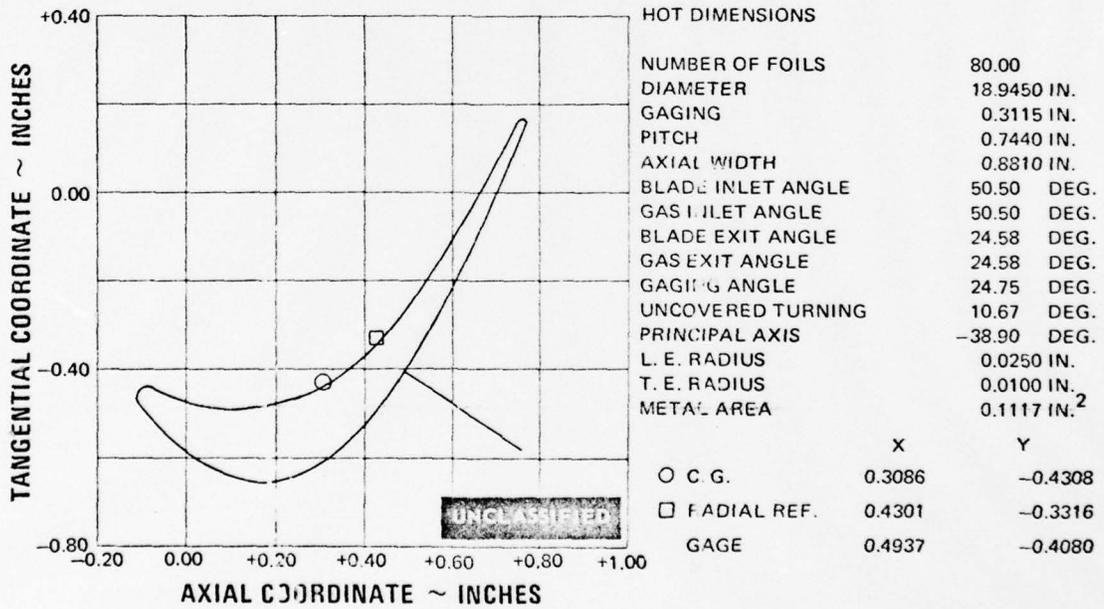


Figure 87 Recontoured Second Vane, Mean Section (CC)

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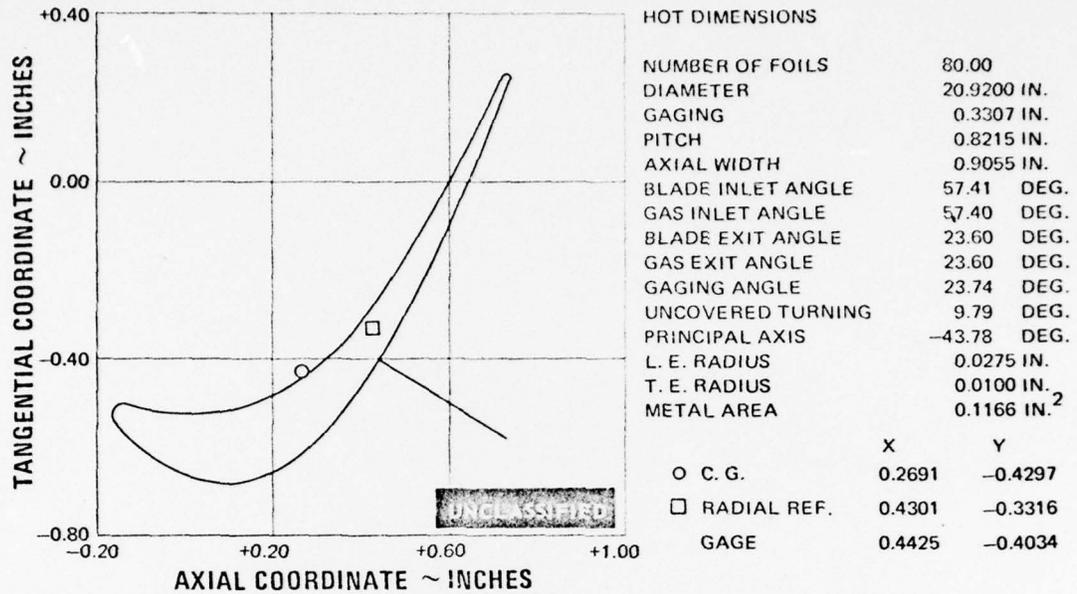


Figure 88 Recontoured Second Vane, 1/4 Tip Section (DD)

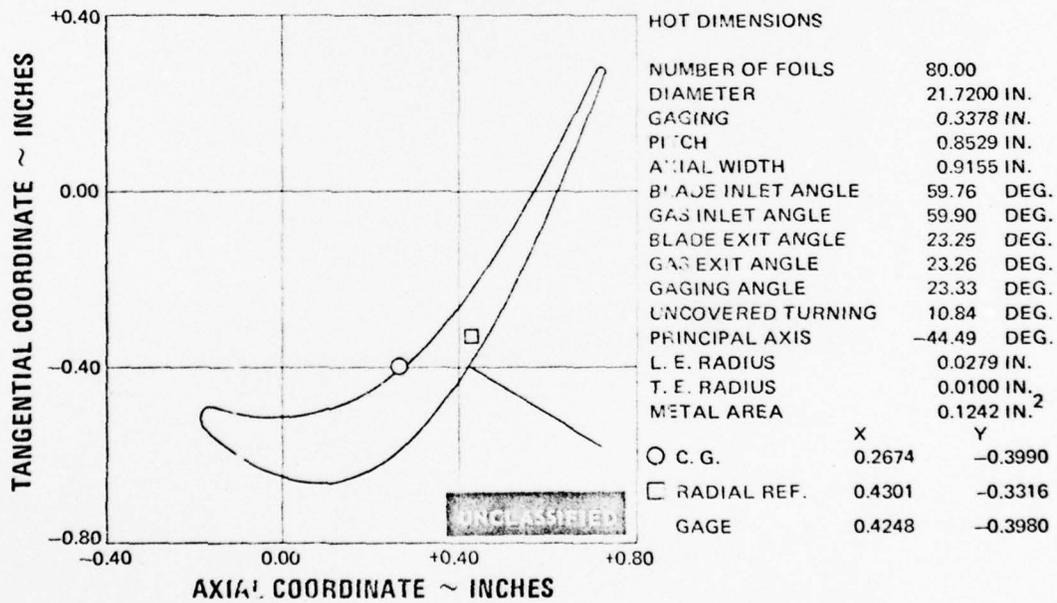


Figure 89 Recontoured Second Vane, Fillet Section (EE)

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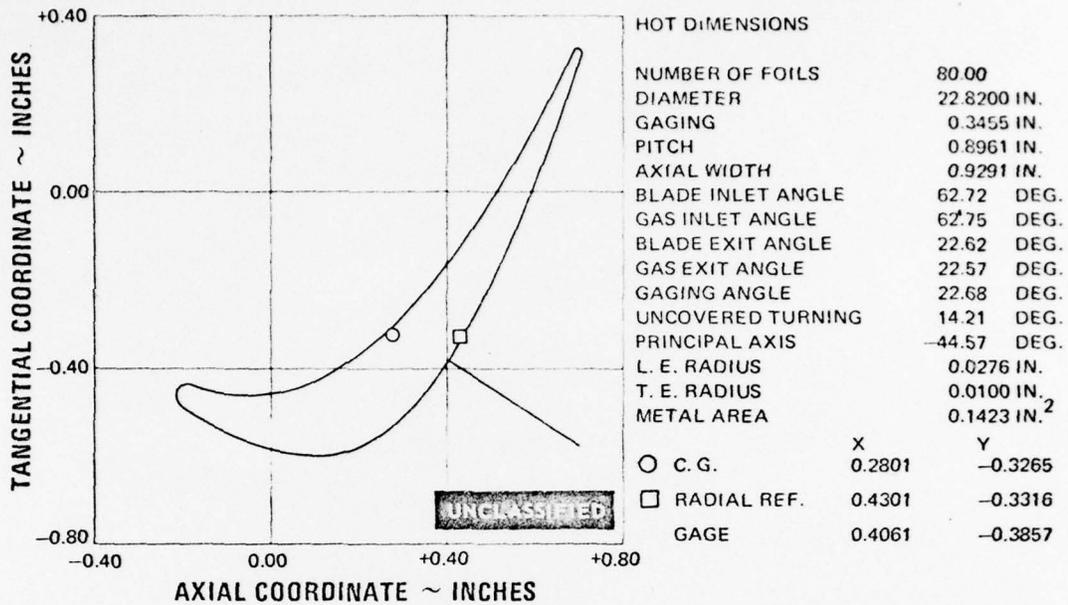


Figure 90 Recontoured Second Vane, Tip Section (HH)

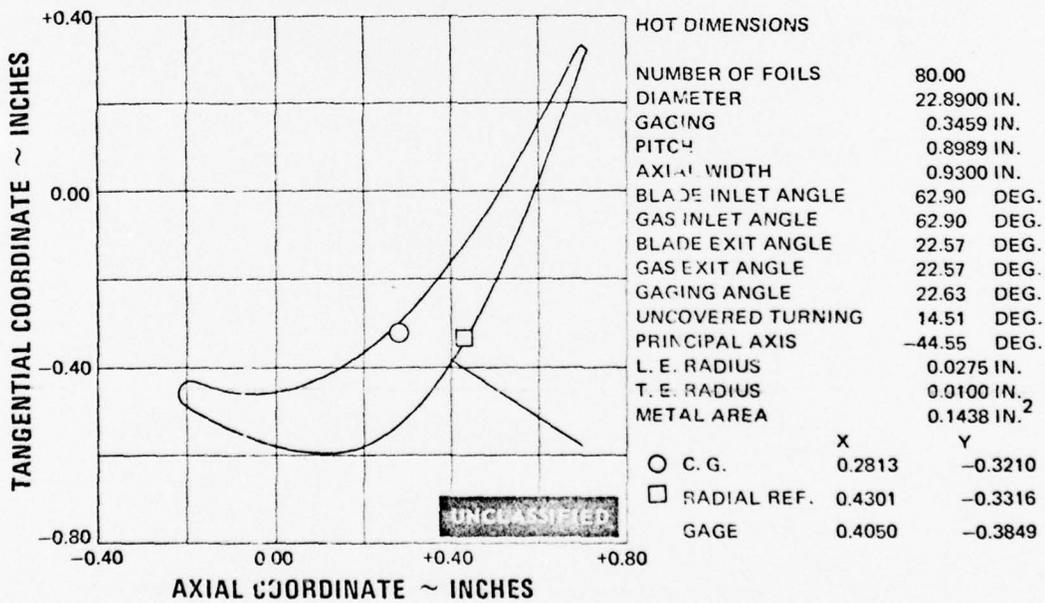


Figure 91 Recontoured Second Vane, Tip Defining Section (GG)



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EXIT GAS ANGLE CONTOURS, DEGREES

Figure 93 Exit Gas Angle Contours. Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. = 0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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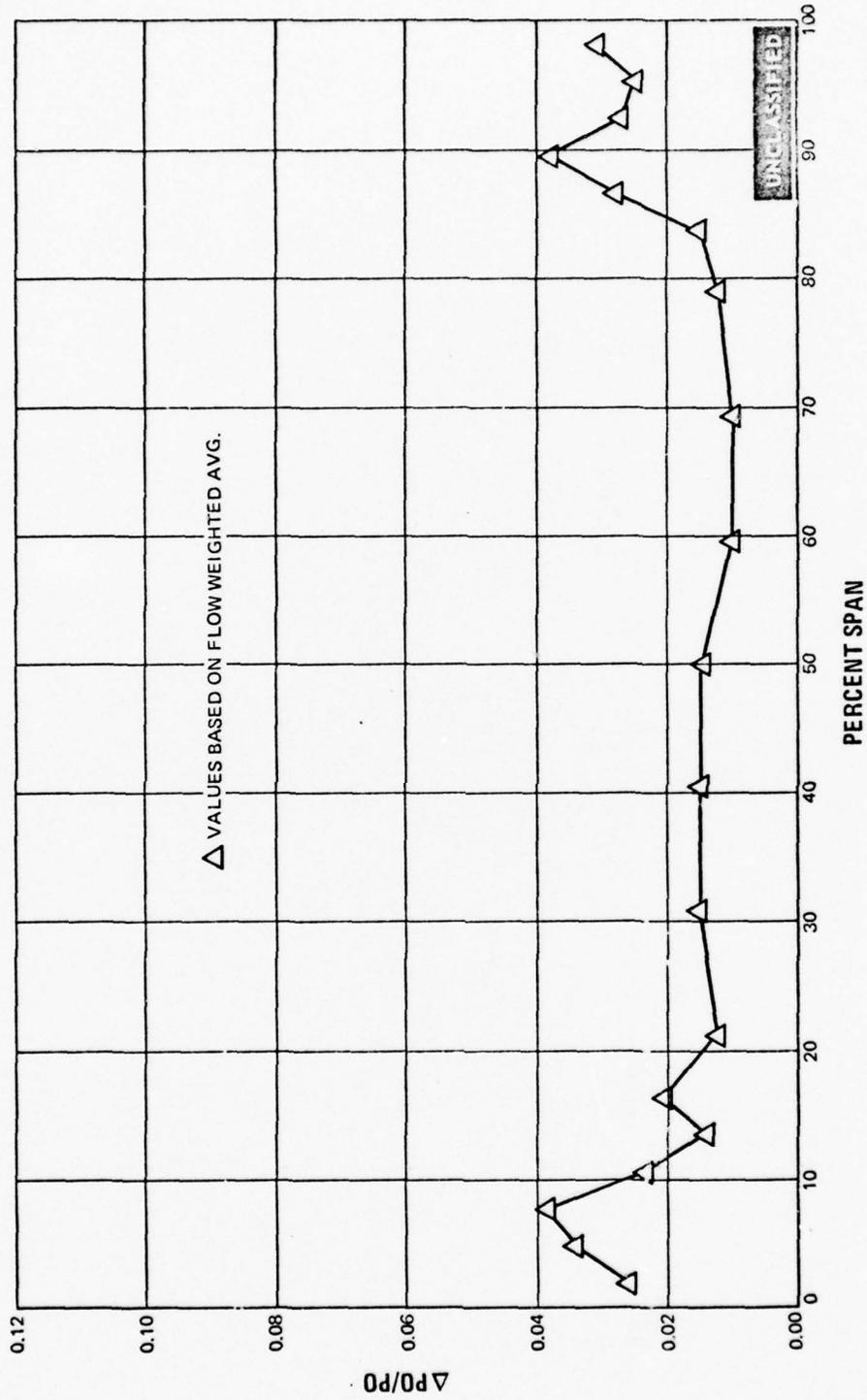


Figure 94 Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

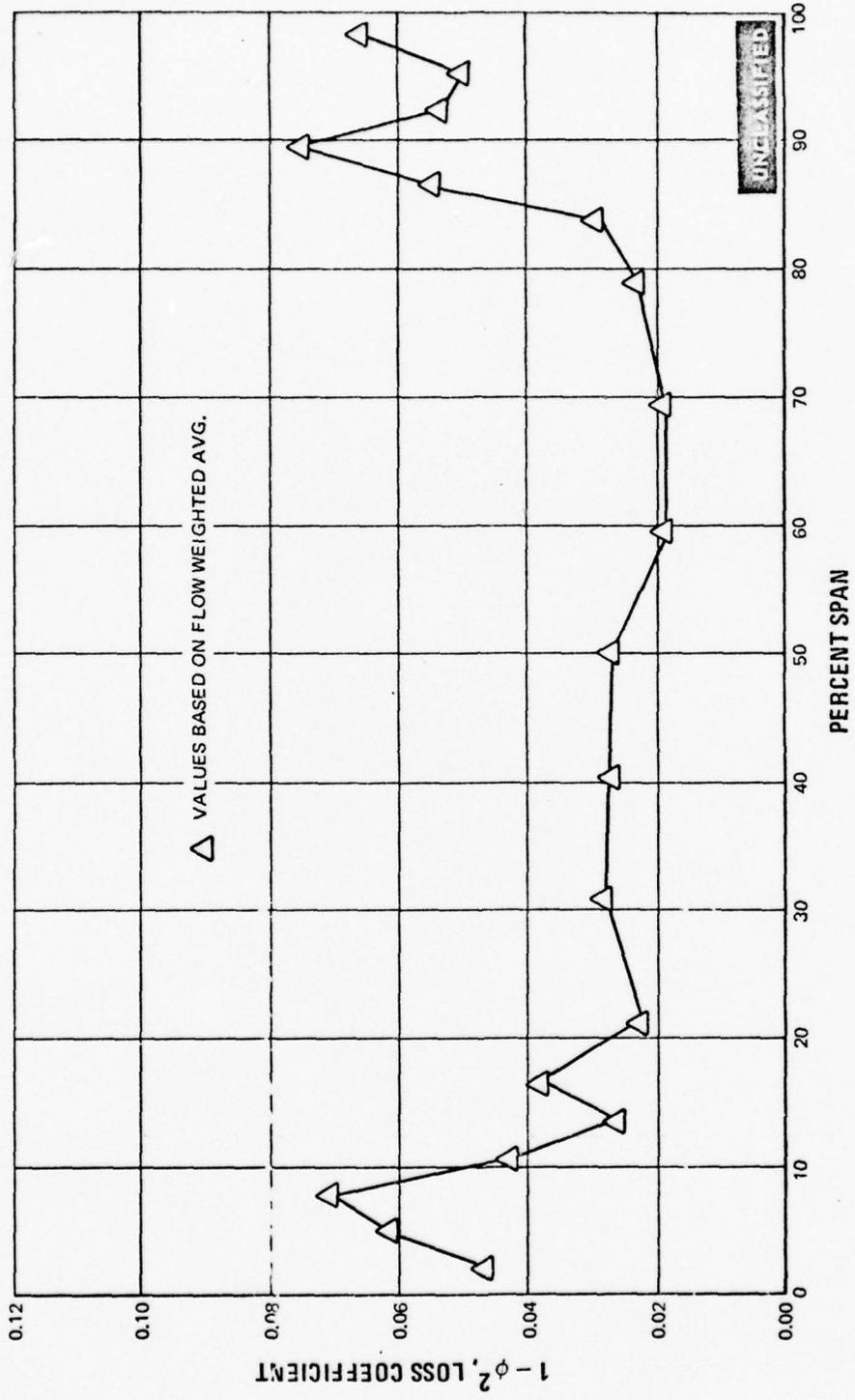


Figure 95 Spanwise Loss Coefficient Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

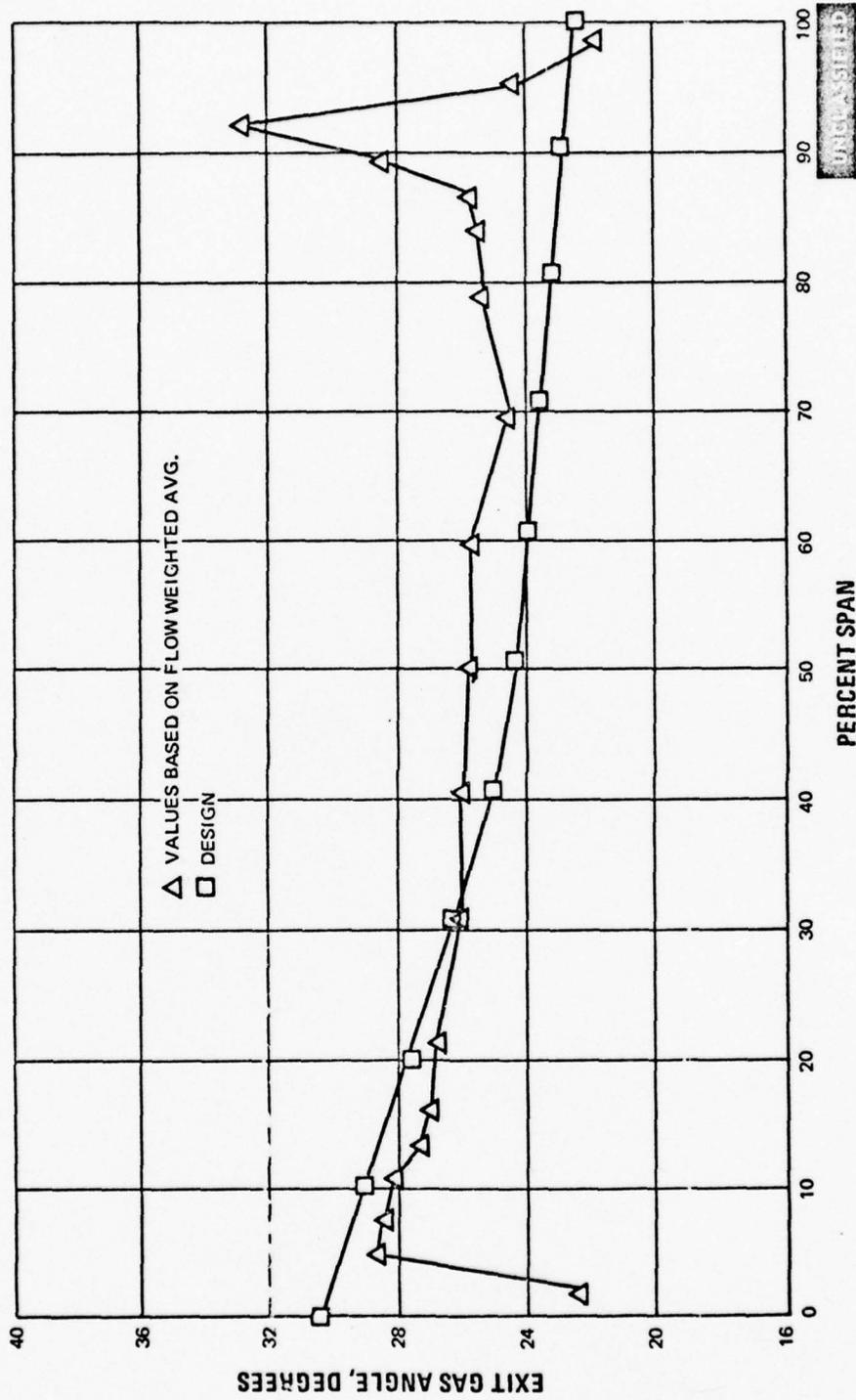


Figure 96 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.863, Recontoured Airfoils With Redesigned Inlet Guide  
Vaness and Optimum Boundary Layer Bleeds

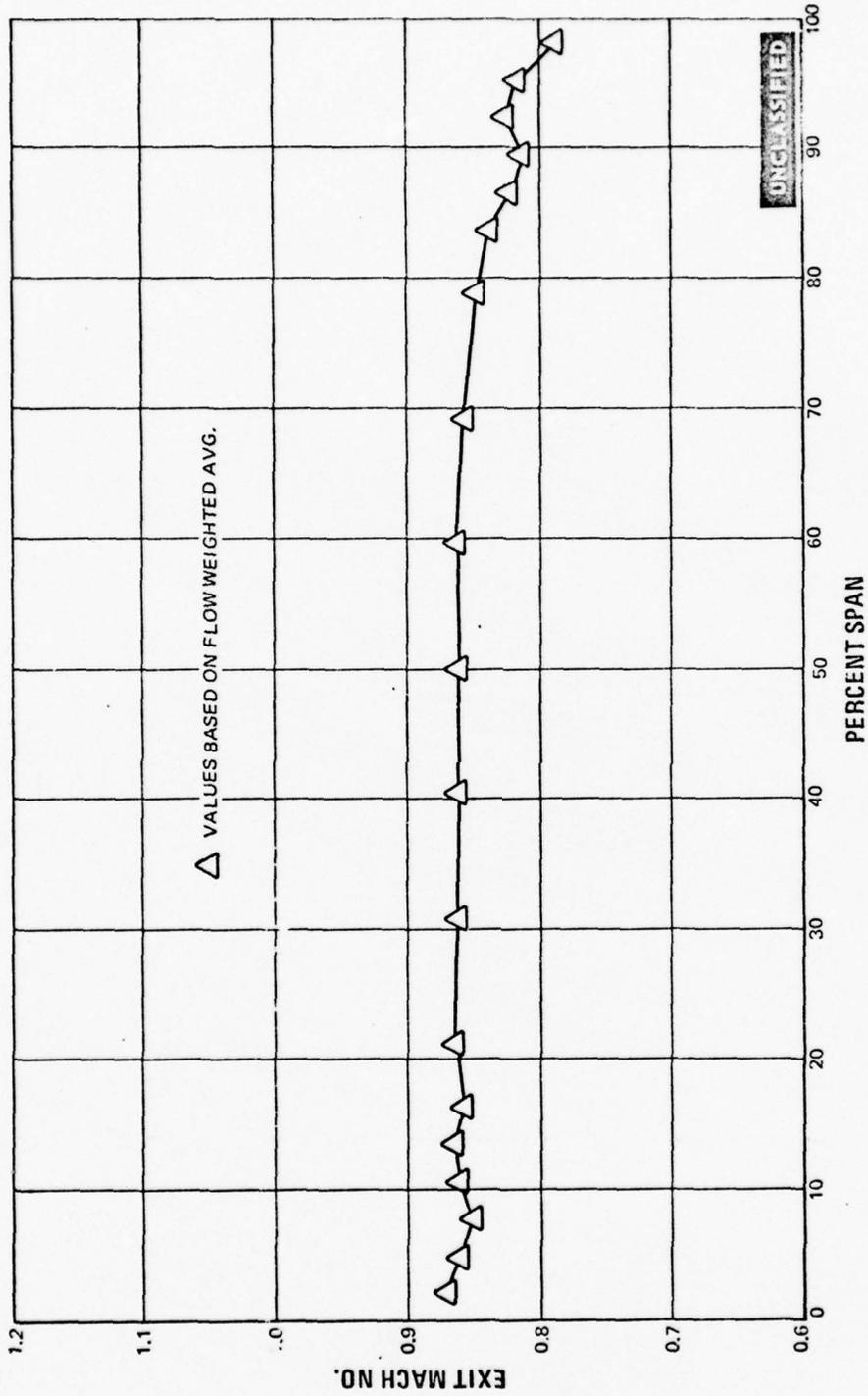


Figure 97 Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.863, Recontoured Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

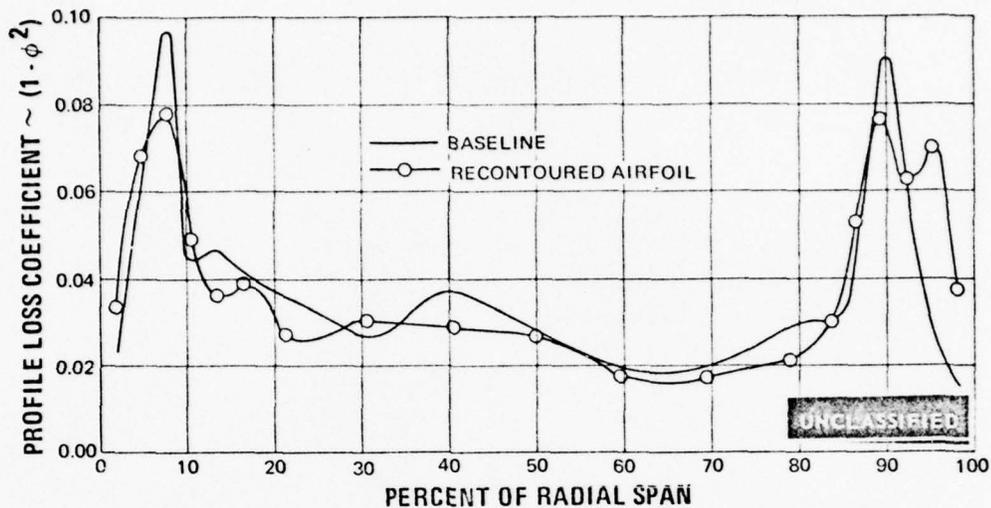


Figure 98 Comparison of Recontoured Airfoil Spanwise Loss Coefficient Distribution with Baseline Values

(U) The measured exit flow angles were almost identical to the baseline values at the root section, while there was an increase in underturning at the tip section. There was no flow separation on either the airfoils, or at the end-wall extensions. The flow visualization test photographs (shown in Figures 99 and 100) verify this conclusion.

(U) The airfoil surface static pressure distributions are shown in Figures 101 through 103 at the root, mean and tip sections. The root section is unloaded and the tip section is slightly more highly loaded than the indicated design predicted values. The reason for this was explained previously in Section II.

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Figure 99 Oil and Graphite Flow Patterns--Second Vane Recontoured Airfoils; Midspan Exit Mach No. =0.863

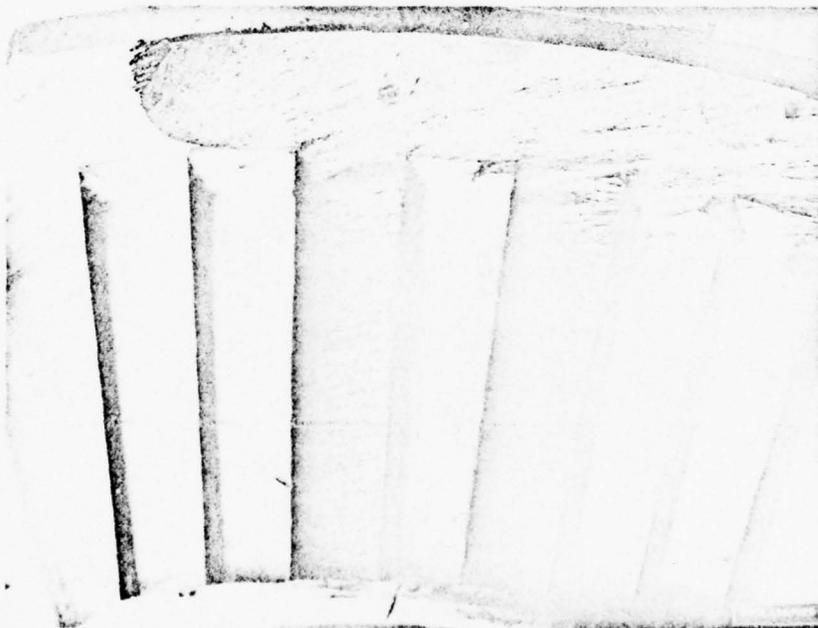


Figure 100 Oil and Graphite Flow Patterns--Second Vane Recontoured Airfoils; Midspan Exit Mach No. =0.863

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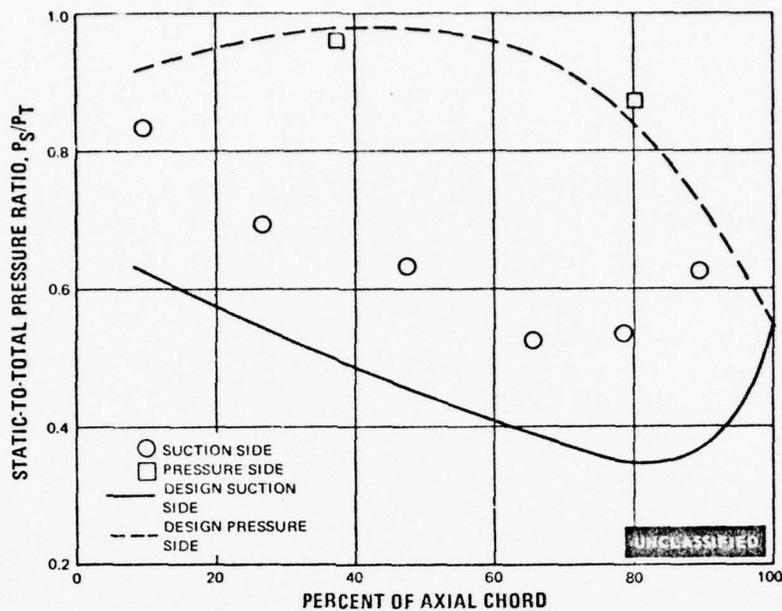


Figure 101 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Screen-Root Section

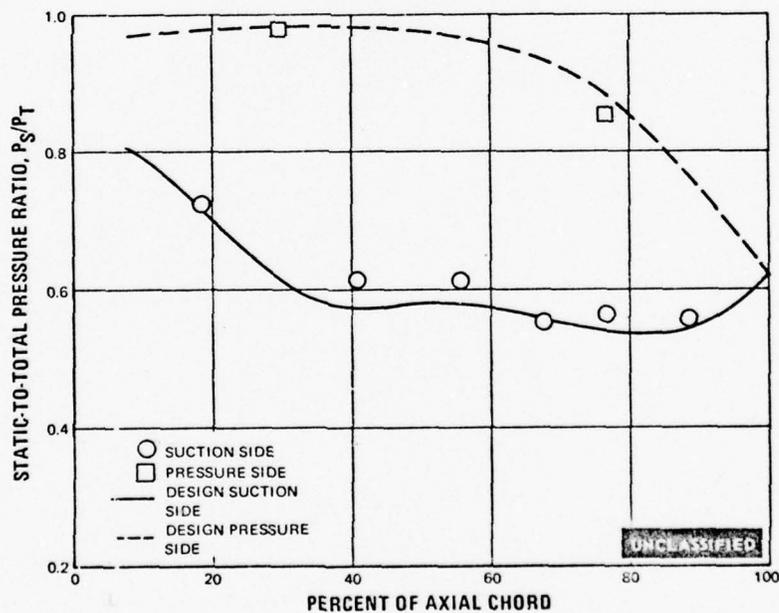


Figure 102 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen-Mean Section

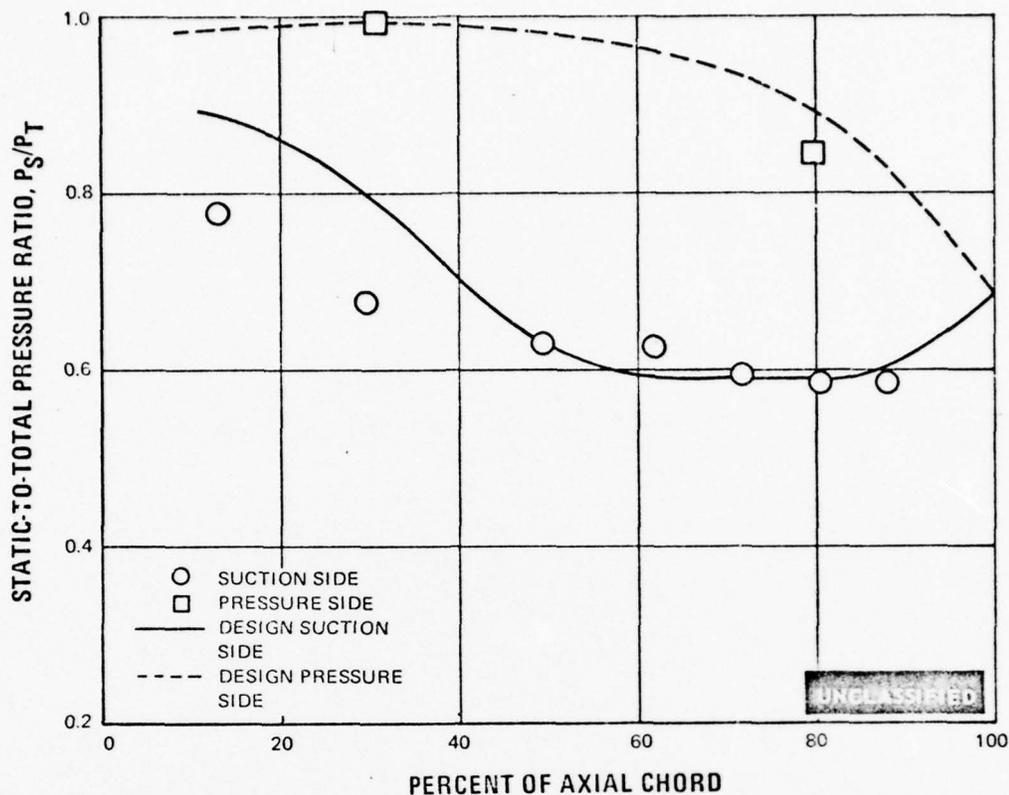


Figure 103 Static-to-Total Pressure Ratio Versus Percent of Axial Chord. Second Vane Recontoured Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section

## 7. END WALL CONTOURING

(U) Another boundary layer control method tested was end-wall contouring. The intent of this design was to reduce the local airfoil loading, and consequently the secondary flow losses, without causing any appreciable disturbance to the flow at other sections of the airfoil or downstream of the airfoil row. Secondary flows occur when the momentum of the fluid near an end-wall has been reduced to a point where it can no longer withstand the pressure-to-suction surface pressure gradient impressed by the potential flow. An attempt was made to reduce the driving pressure gradient forces via a suitable end-wall design.

(U) The design of the end-wall contour was based on two computations. The first was the calculation of the pressure distribution around an airfoil of the desired profile on a plane surface. This program allows streamtube height variations, but is not able to account for radial pressure gradients. The second was the calculation of the axisymmetric, intrablade flow behavior. The guidelines established during the design required that the end-wall contour must decrease the local airfoil loading, must not cause separa-

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tion on the end-wall, must not cause an increase of positive incidence by more than 5 degrees, and must not increase the adverse pressure gradient on the uncovered portion of the airfoil suction surface. Each of these could be separately estimated by the application of the two available procedures, although correct solution via a genuine three-dimensional calculation is not yet possible.

(U) The best and final contour was one with sinusoidal inlet and exit wall height distribution, having the leading and trailing edges intersecting at the inflection points. The end-wall contours for both the inner and outer walls of the second vane airfoil are shown in Figures 104 and 105. The inside-diameter wall contour was the one that was actually designed, and the outside-diameter wall contour was scaled from the inside-diameter wall design. The design studies indicated that the end-wall contouring using depths large enough to produce a significant reduction in the tangential pressure difference should not be accomplished by new contours contained completely within the airfoil row. Also, the most acceptable contour was one designed to counteract the airfoil blockage effects by increasing the annulus area in the leading edge region. The inlet and exit sections were connected by a constant area section starting at approximately 24 percent of axial chord and ending at approximately 76 percent of axial chord. The actual manufactured contour is also indicated in these figures, and deviations from the design contour are noted.

(U) The performance data for this airfoil are shown in Figures 106 through 111. These plots are of the same parameter as those shown for the previous tests. The data in these figures is presented at a midspan exit Mach number of 0.843, the value nearest the design point. Data were also taken at midspan exit Mach numbers of 0.79 and 0.988. Analysis of the design point data indicates that there was a negligible increase in loss level at the root section, and a large increase in loss coefficient at the tip section, as compared to the baseline values. The spanwise integrated value from the midspan to the inside-diameter wall was 0.0374, and from the midspan to the outside-diameter wall was 0.0482. The corresponding baseline values were 0.0353 and 0.0345, respectively. The overall integrated spanwise loss coefficient for the end-wall contoured airfoil was 0.0428, as compared to 0.0349 for the baseline tests. A comparison plot of the spanwise loss coefficient for both the end-wall contoured, and the baseline, is shown in Figure 112. The loss coefficient showed a decrease of loss with Mach number, the values decreasing from 0.0444 to 0.0386, as Mach number decreased from 0.79 to 0.988. This effect is mostly due to an increase in Reynolds Number as explained in Part 3 above.

(U) The spanwise integrated exit gas flow angle (Figure 107) indicated a large underturning at the root and tip sections. Flow visualization photographs of this test are shown in Figures 113 and 114.

(U) The airfoil surface static pressure distributions are shown in Figures 115 through 117 at the root, mean and tip sections. The predicted curves shown on these plots are those for the baseline airfoil and not for the contoured end-wall configuration. As previously noted, the tip section wall was not specifically designed. End-wall contouring techniques may well succeed when three-dimensional methods for potential flow and boundary layer calculations are available.

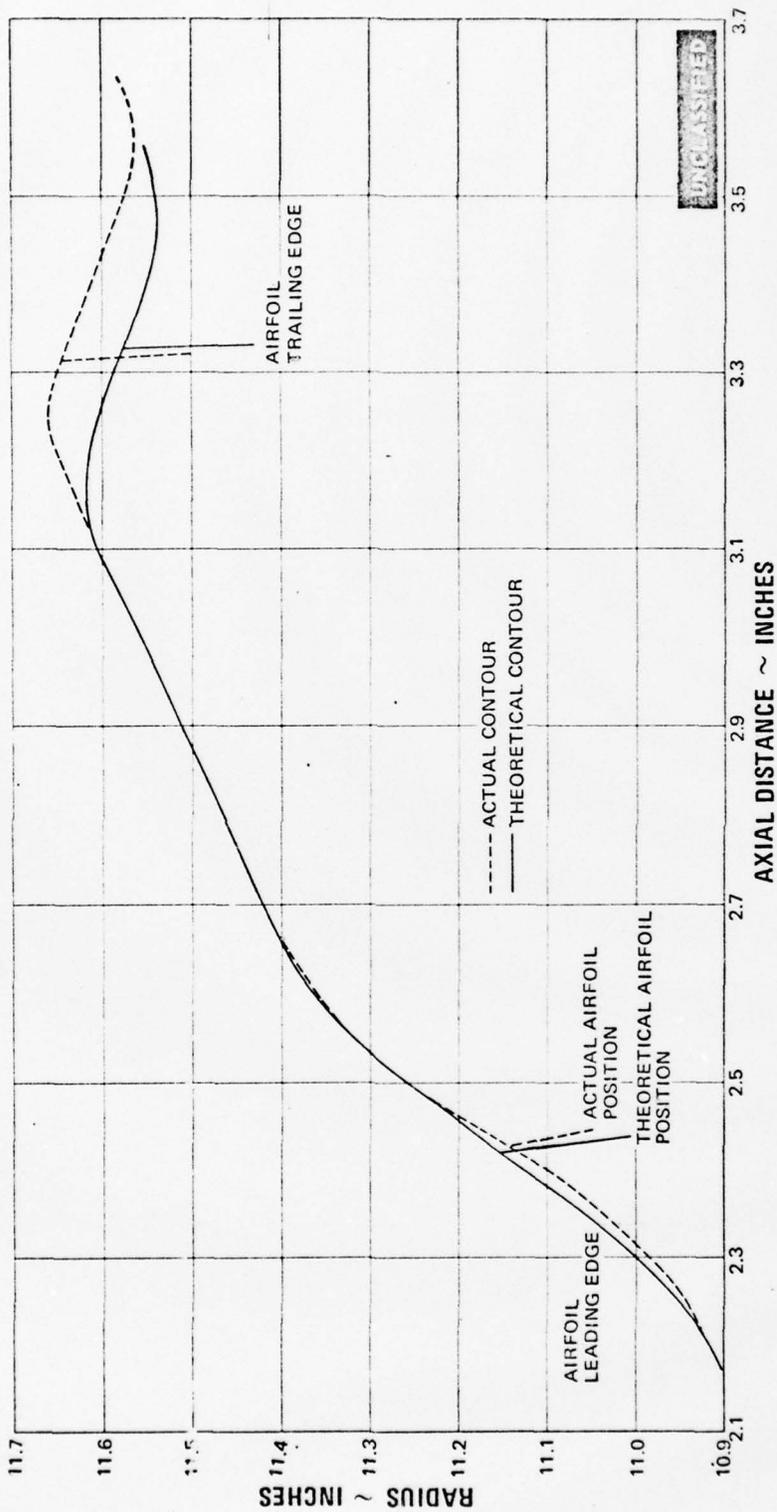


Figure 104 Profile for End Wall Contouring, Inside Diameter Wall

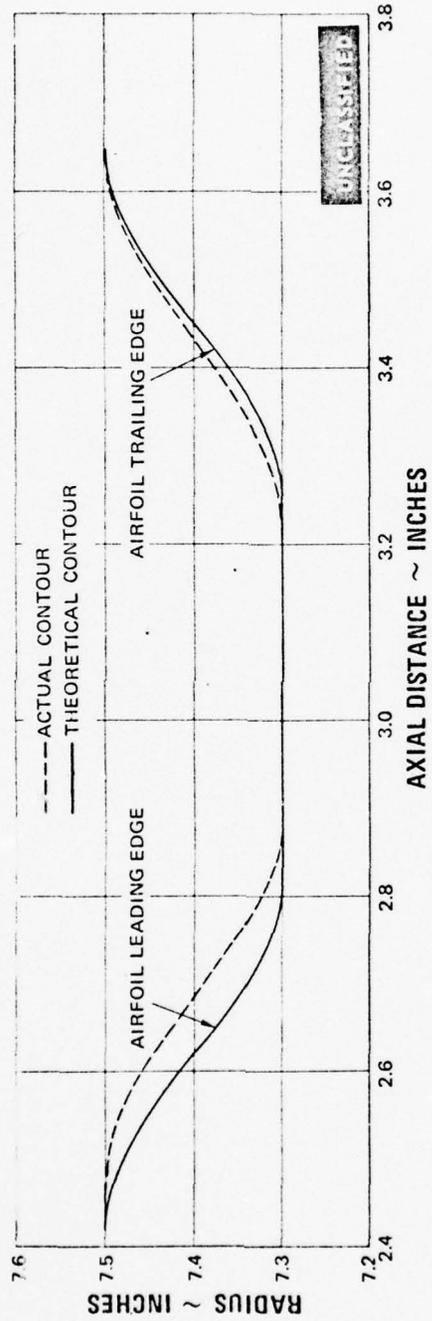


Figure 105 Profile for End Wall Contouring, Outside Diameter Wall



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EXIT GAS ANGLE CONTOURS, DEGREES

Figure 107 Exit Gas Angle Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. = 0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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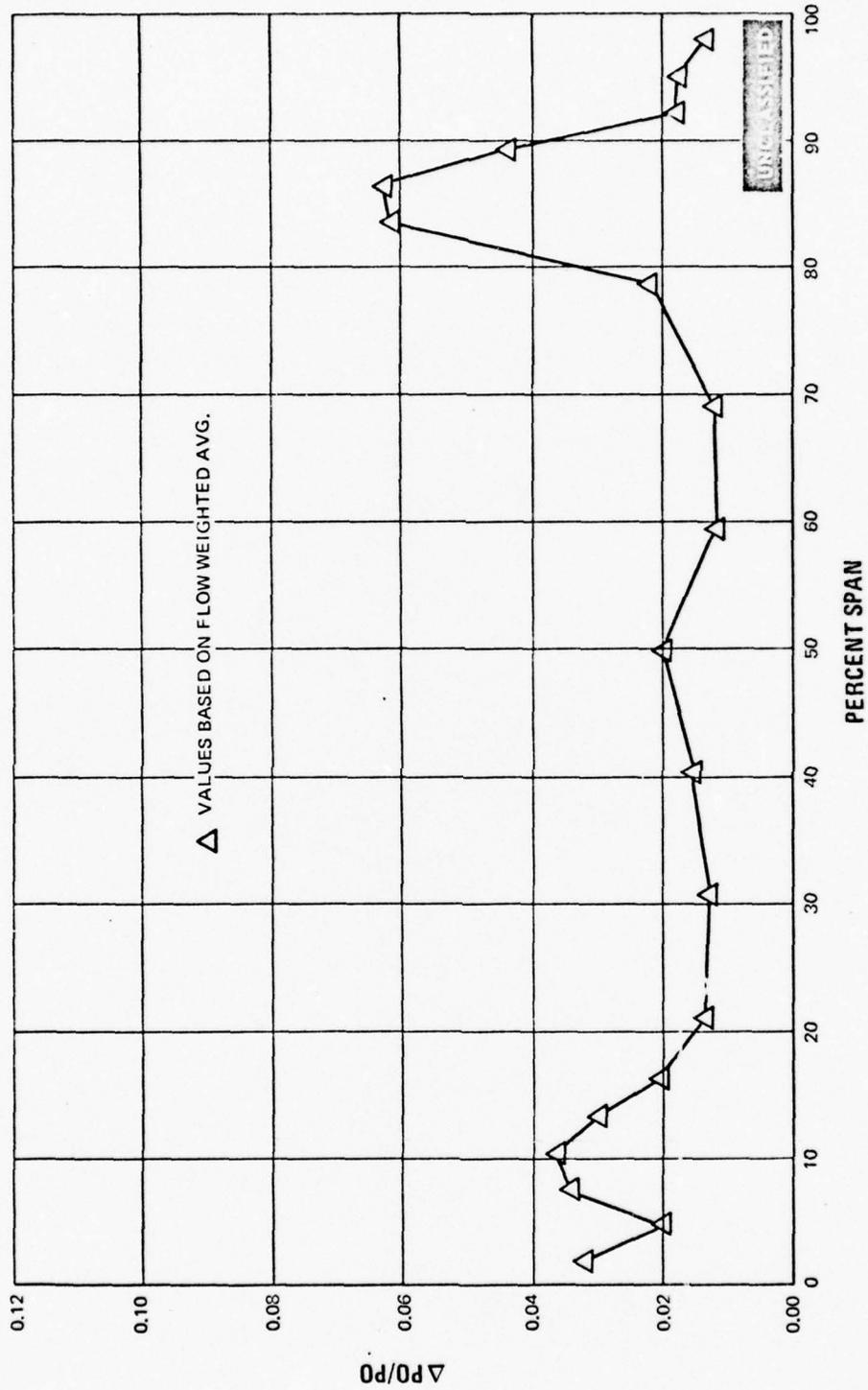


Figure 108 Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes  
and Optimum Boundary Layer Bleeds

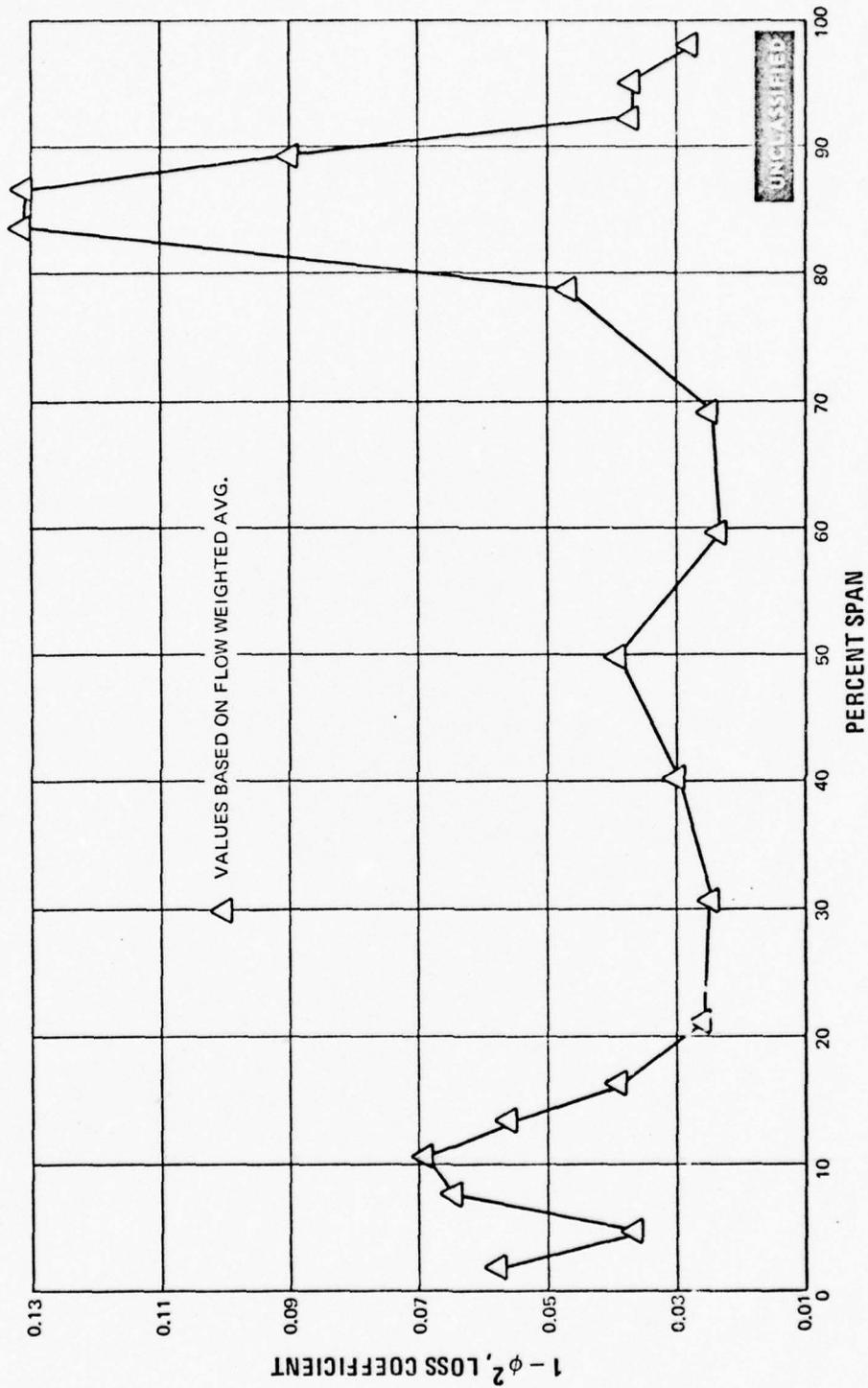


Figure 109 Spanwise Loss Coefficient Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

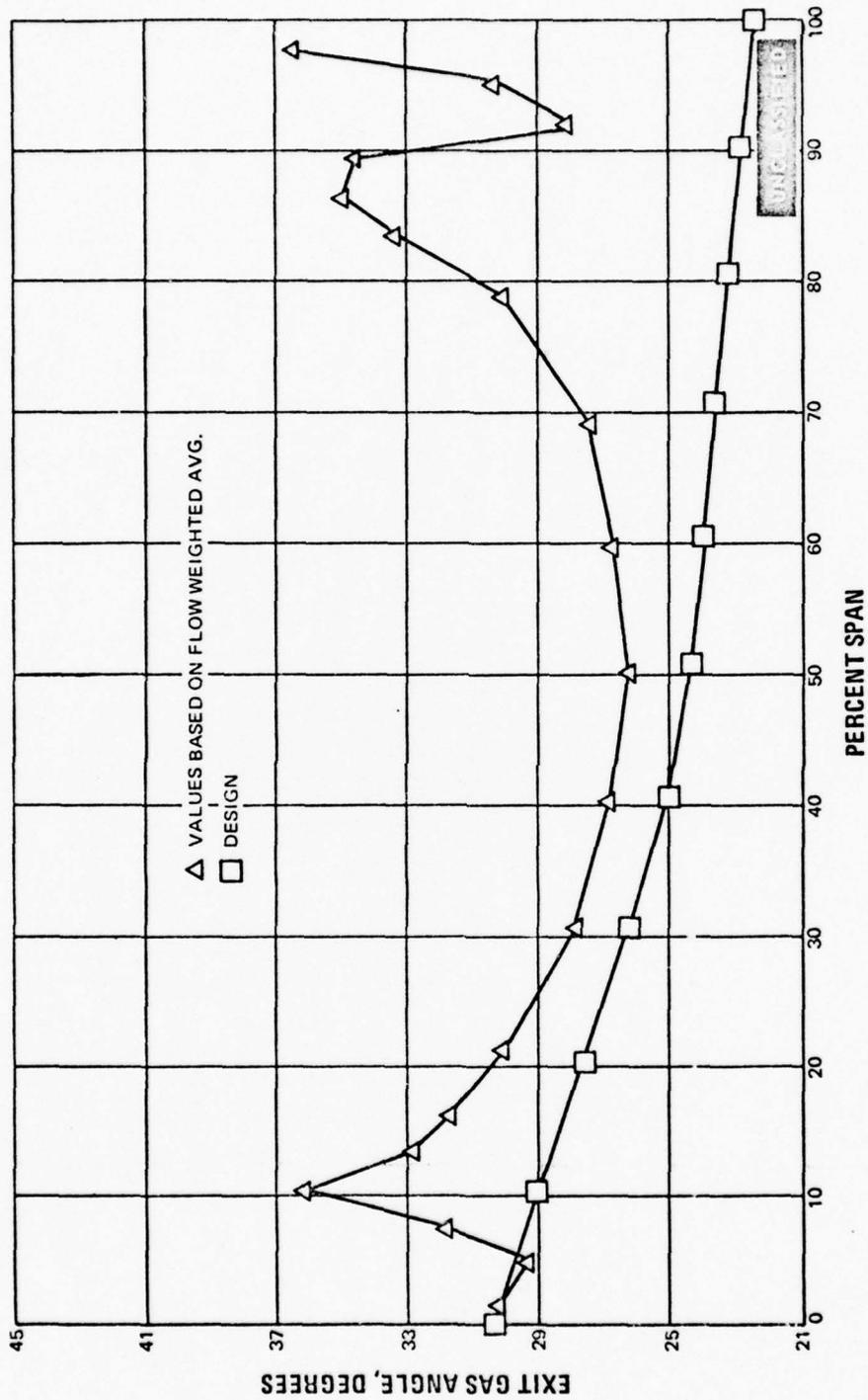


Figure 110 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

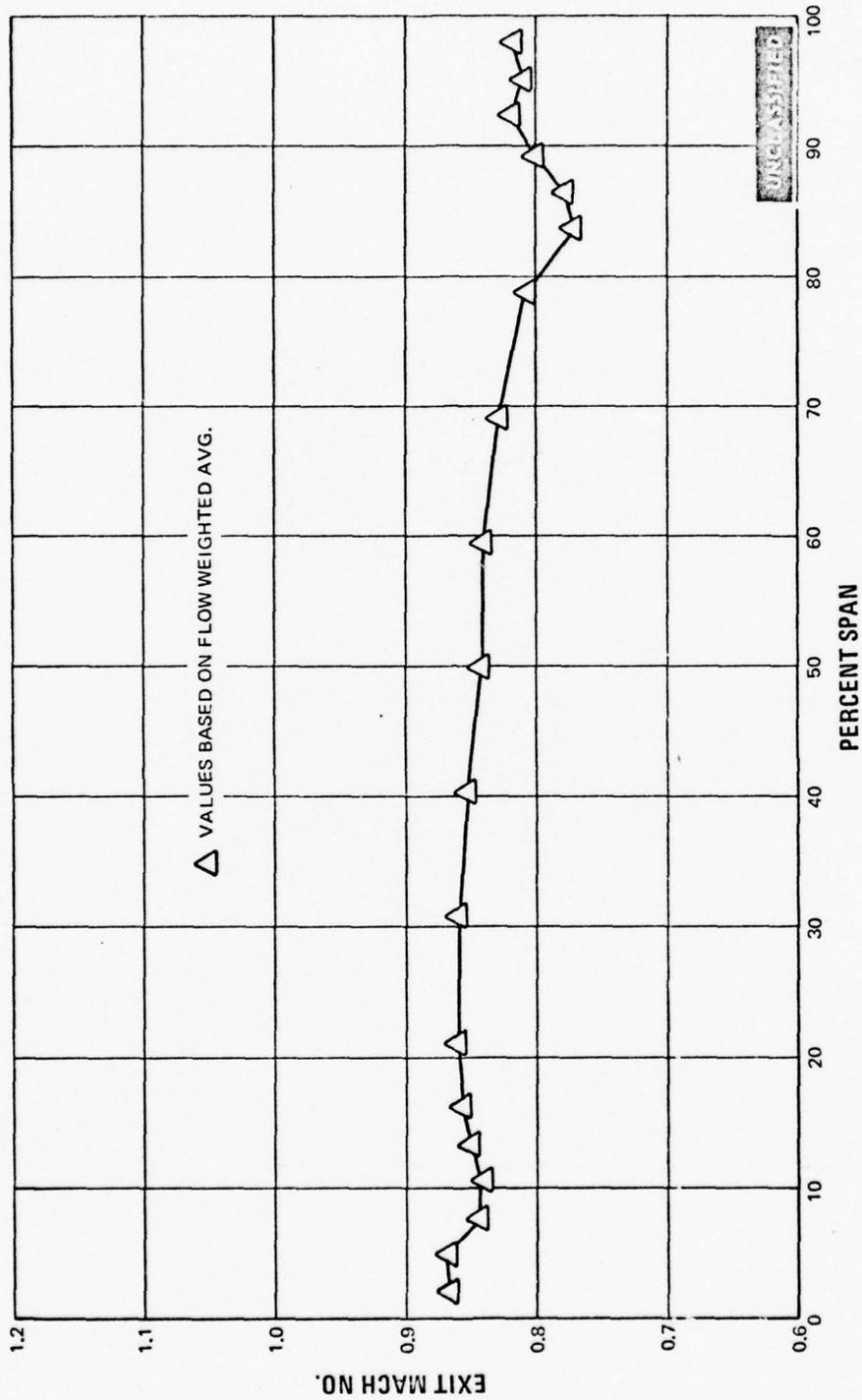


Figure 111 Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.843, Recontoured Endwalls With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

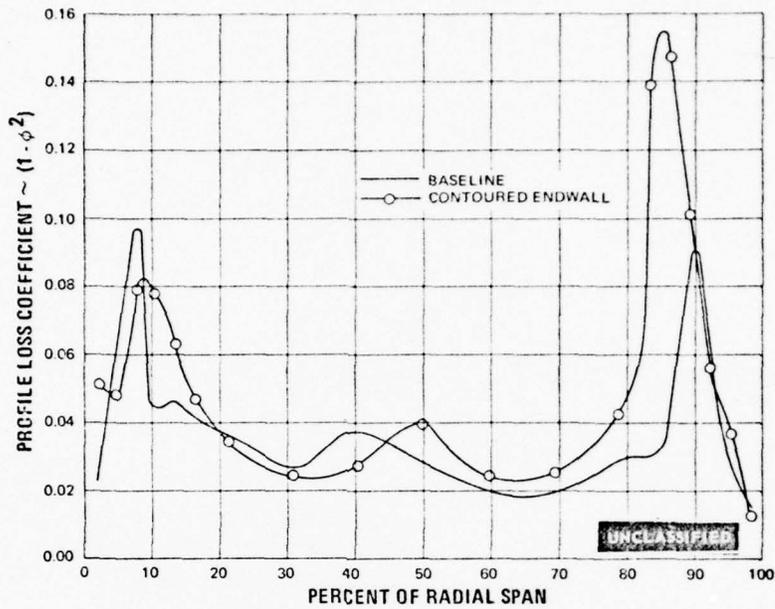


Figure 112 Comparison of Recontoured End Wall Spanwise Loss Coefficient Distribution with Baseline Values



Figure 113 Oil and Graphite Flow Patterns—Second Vane with End Wall Contouring; Midspan Exit Mach No. =0.843

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Figure 114 Oil and Graphite Flow Patterns--Second Vane with End Wall Contouring; Midspan Exit Mach No.  $\approx 0.843$

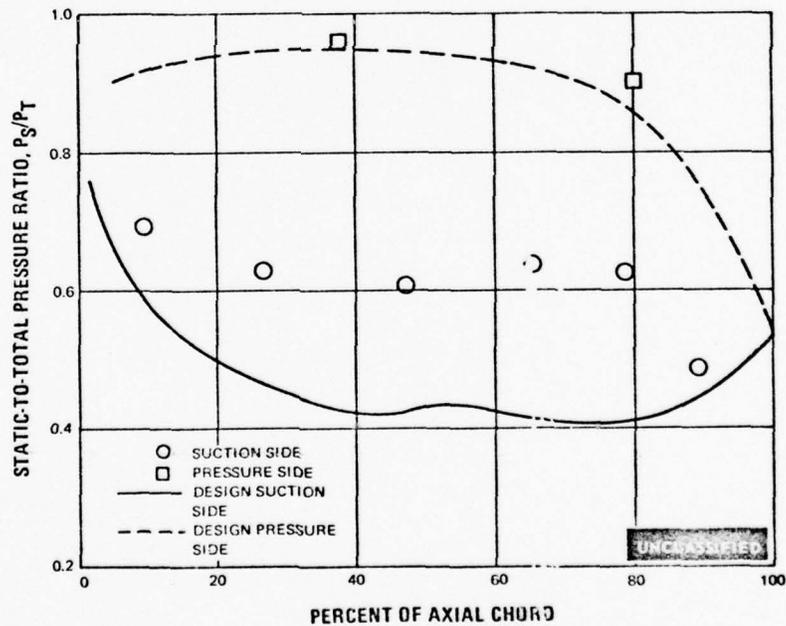


Figure 115 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen--Root Section

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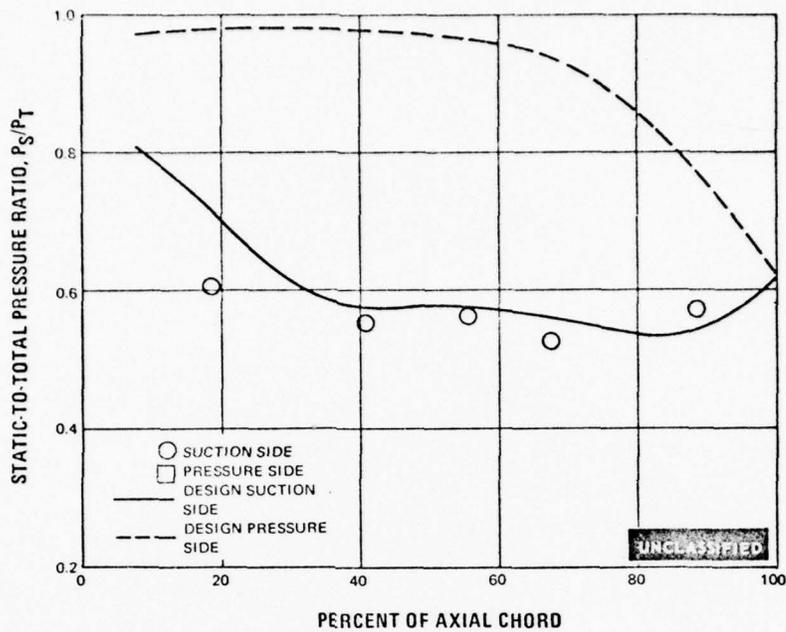


Figure 116 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Mean Section

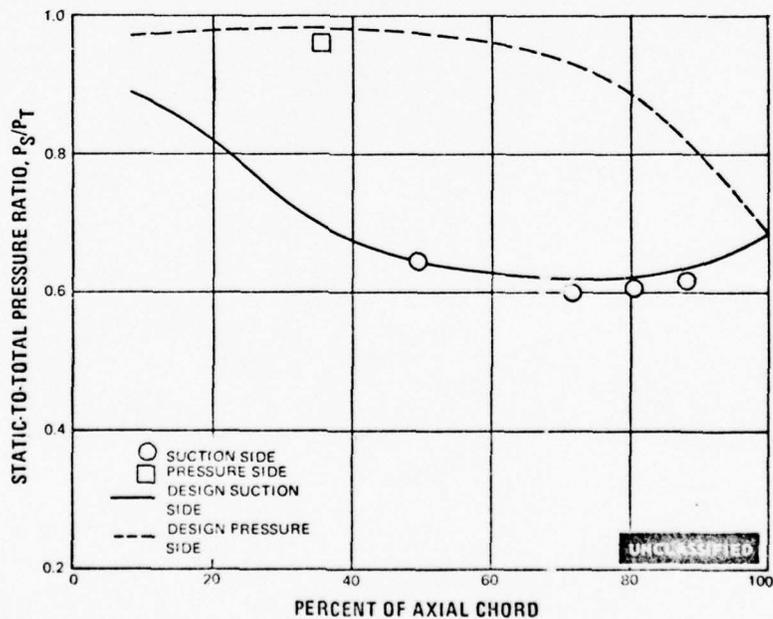


Figure 117 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recontoured End Walls With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section

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8. RECAMBERED AIRFOILS

(U) The final boundary layer control technique tested was the locally recambered second vane airfoil. Local recambering, to reduce secondary losses at the root and tip sections of the second vane, required a streamline analysis of the entire study turbine. The inlet airfoil angles were held constant to allow the use of the same inlet hardware. The tip section was closed or reduced by 5 degrees, while the root section was opened or increased by 5 degrees. This technique was used since the ends behave essentially independently of one another. The camber changes were then curved-line-faired into the original camber at the 25 and 75 percent span sections as reported in the Reference 3 Report. The streamline analysis indicated that, in order to maintain the same stage work and reaction level, the second stage blade would have to be opened by increasing the exit gas angle by 0.5 degree across the span.

(U) Comparison plots with baseline airfoils at the root and tip section are shown in Figures 118 and 119. The elevation of the recambered airfoil with the reference sections are shown in Figure 83 and the section profiles are presented in Figures 120 through 127.

(U) The performance data for the recambered airfoils are given in Figures 128 through 133. This data is shown at a midspan exit Mach number of 0.880. Data were also taken at Mach numbers of 0.823 and 1.033. The resulting spanwise loss coefficients are compared with the baseline values in Figure 134 at the design Mach number.

(U) The overall integrated loss coefficient for the recambered airfoil was 0.0329 as compared to 0.0349 for the baseline value. The root section showed a significant reduction (0.0286 versus 0.0353), while the tip section indicated a slight increase (0.0372 versus 0.0345), compared to baseline values. Flow visualization photographs of these airfoils are shown in Figures 135 and 136. The measured flow angles at the tip section indicate attached flow with only a slight underturning from the design values. The root section data indicate a large increase in underturning over baseline values, but there is no indication of flow separation on the flow visualization photographs.

(U) Airfoil surface static pressure distributions are shown in Figures 137 through 139. The predicted curve for the recambered airfoil section is also shown. The same comments apply to these data as in previous discussions of airfoil surface static pressures.

(U) It is especially comforting that all the observed results of this test are in complete accord with reasonable expectations. In short, the application of this method to turbine design should offer no special difficulties.

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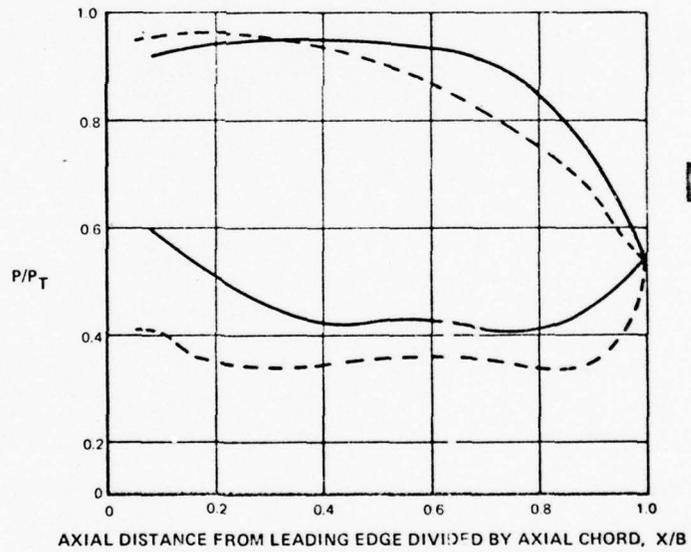
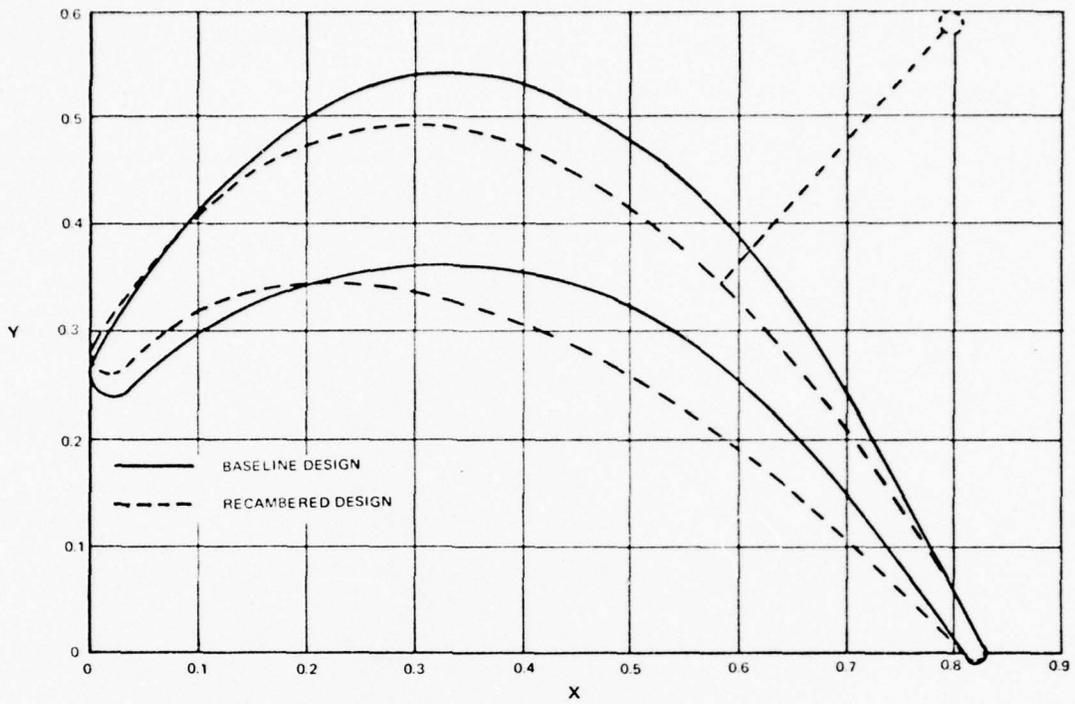
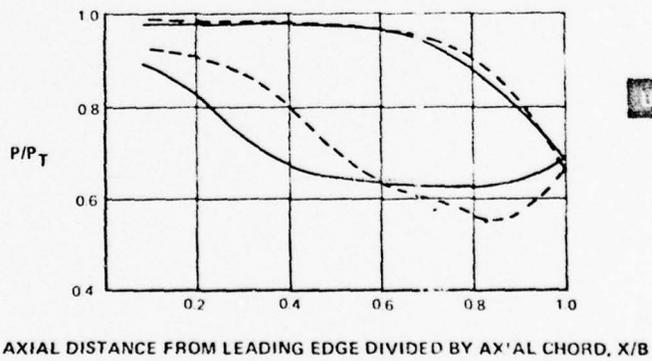
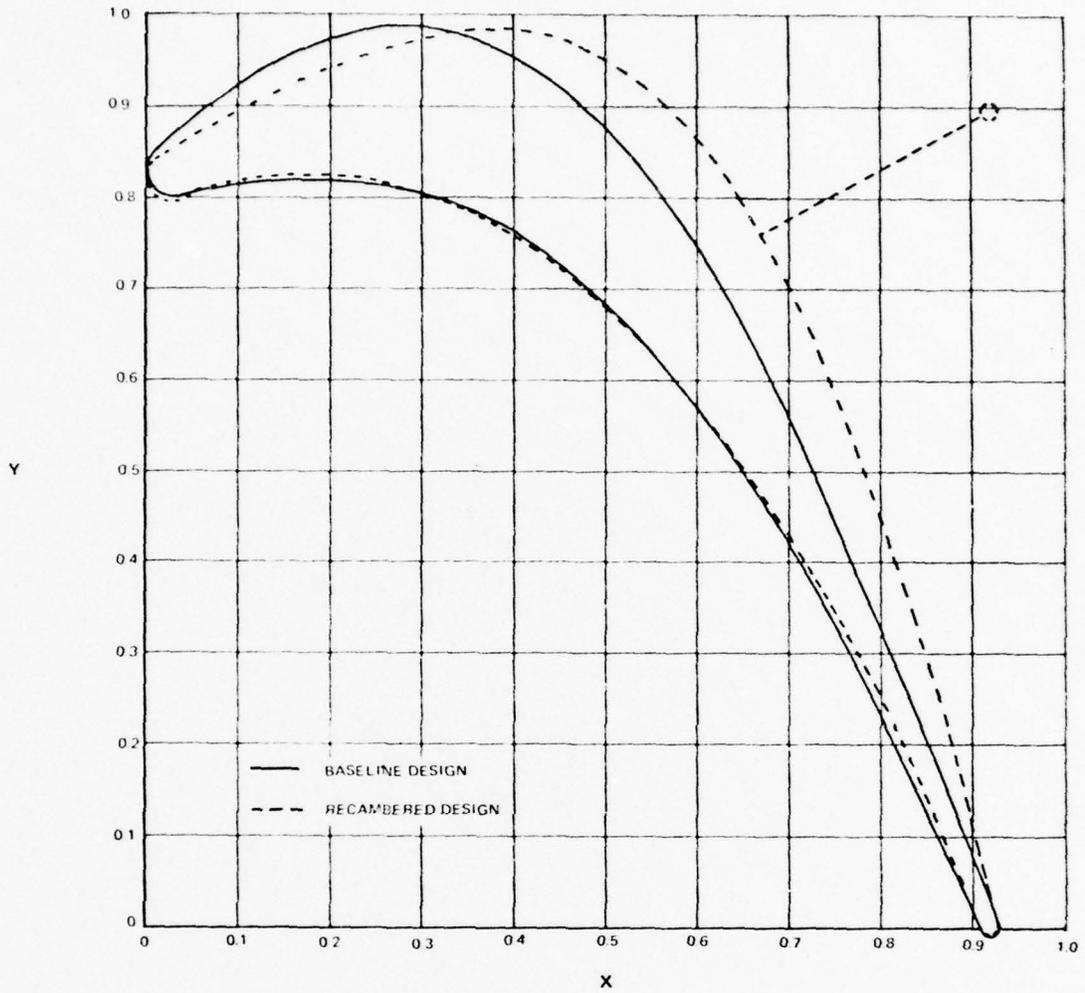


Figure 118 Second Vane Root Section Recambering

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Figure 119 Second Vane Tip Section Recambering

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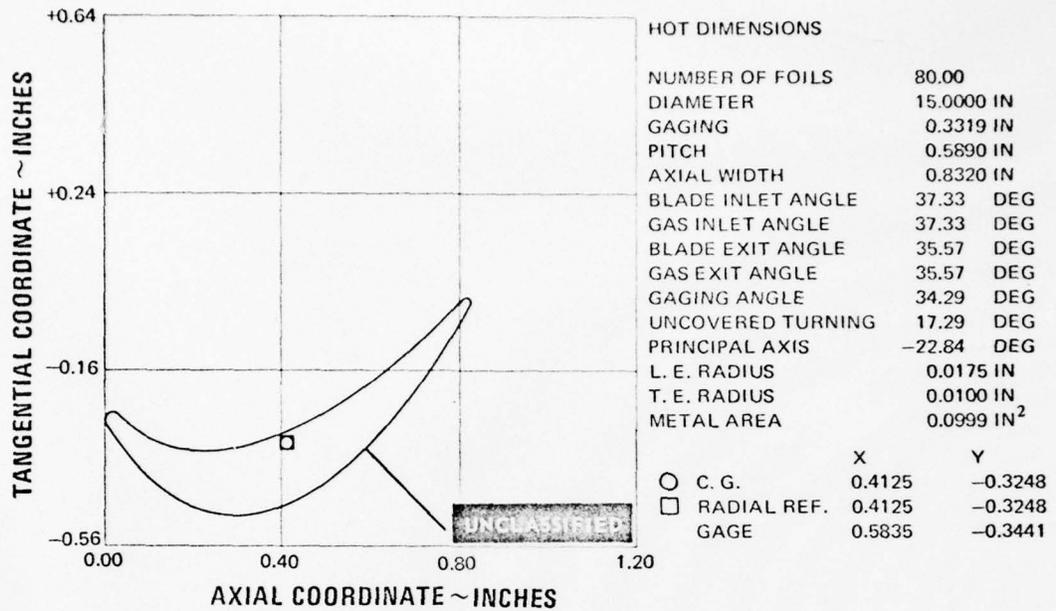


Figure 120 Recambered Second Vane, Root Section (FF)

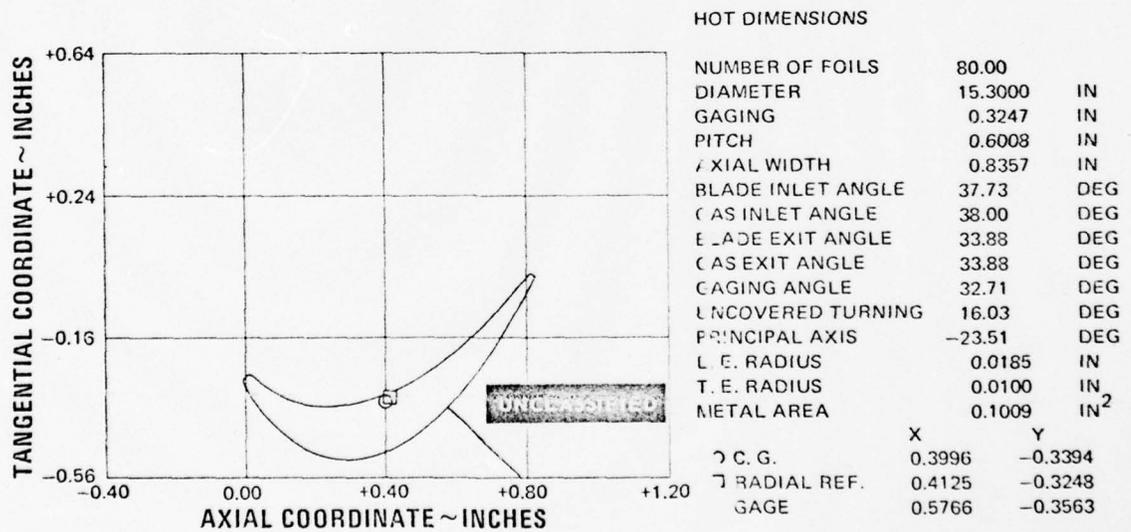


Figure 121 Recambered Second Vane, Root Fillet Section (AA)

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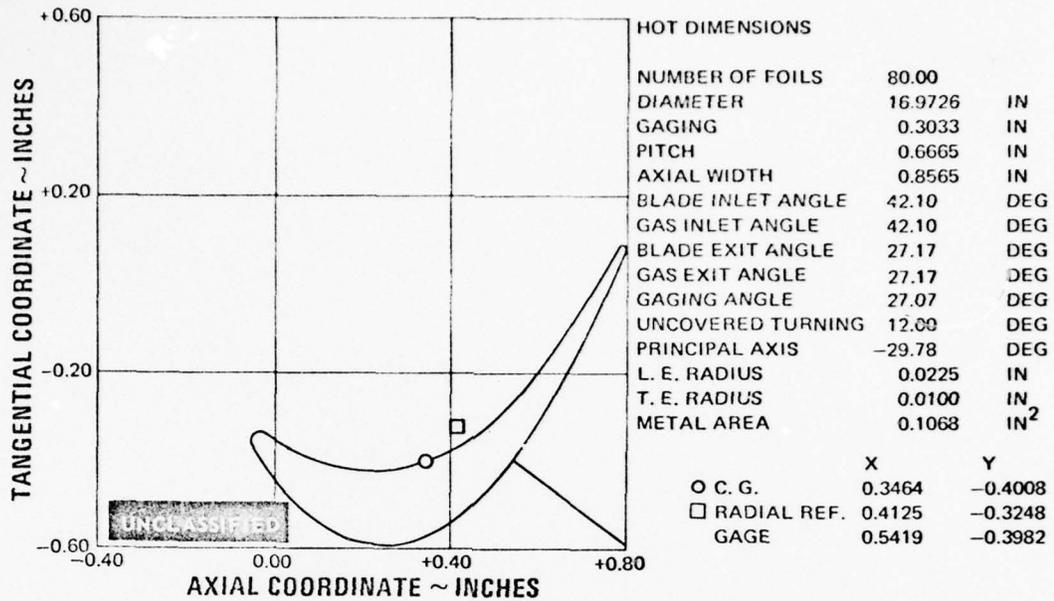


Figure 122 Recambered Second Vane, 1/4 Root Section (BB)

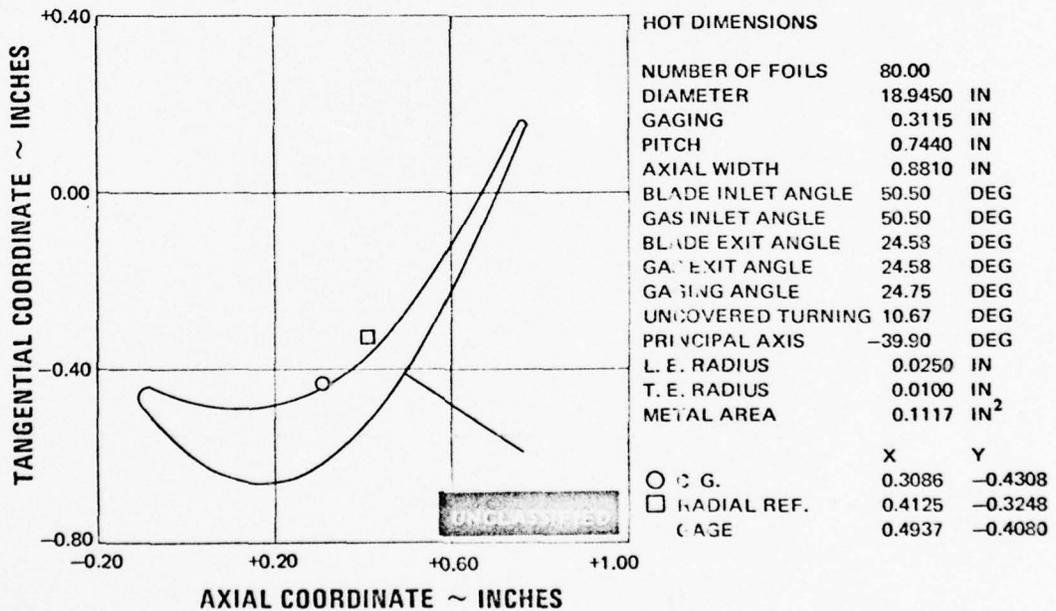


Figure 123 Recambered Second Vane, Mean Section (CC)

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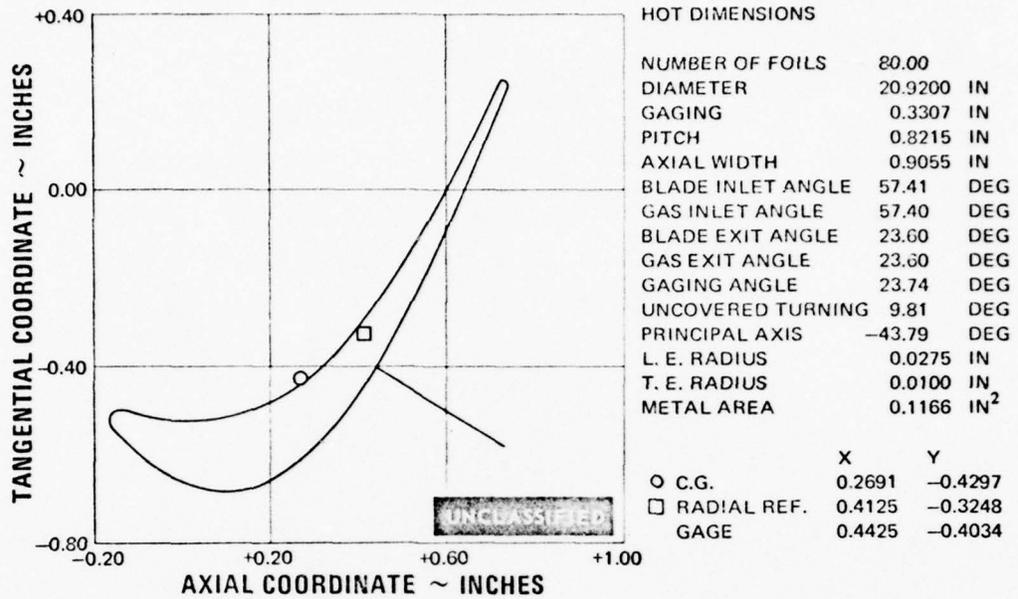


Figure 124 Recambered Second Vane, 1/4 Tip Section (DD)

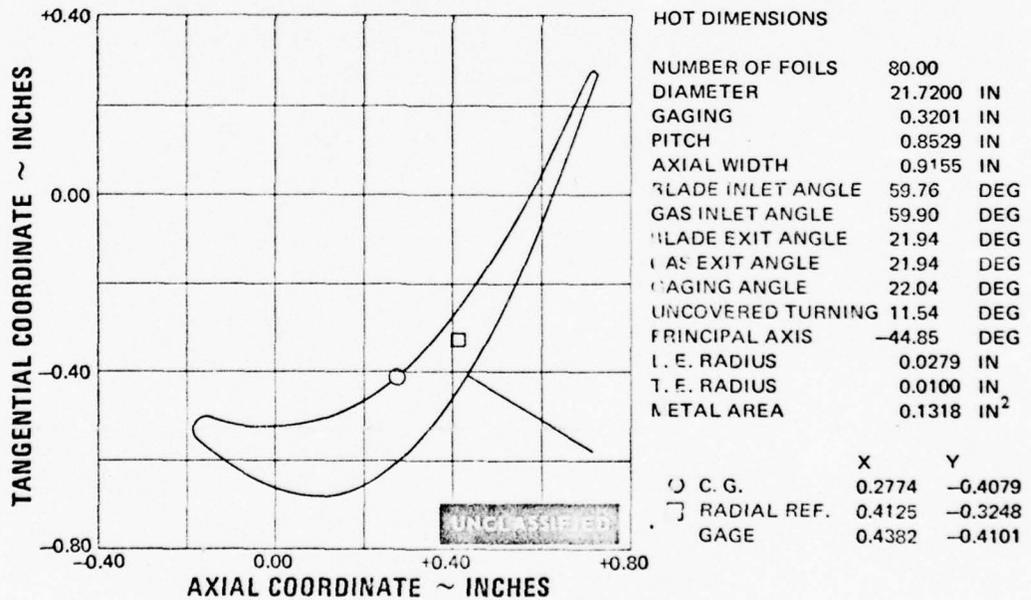


Figure 125 Recambered Second Vane, Fillet Section (EE)

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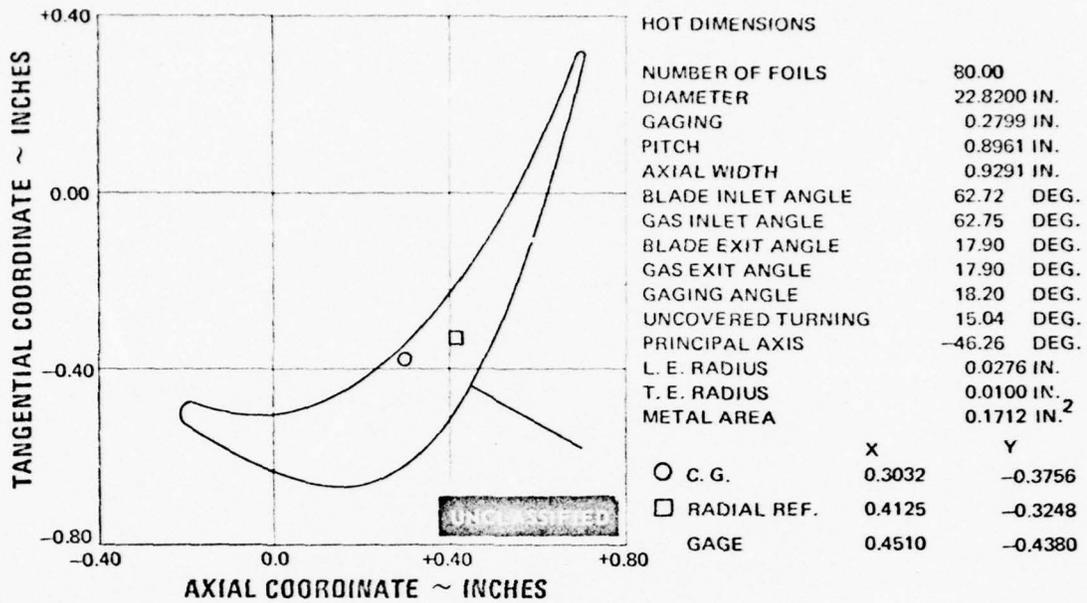


Figure 126 Recambered Second Vane, Tip Section (HH)

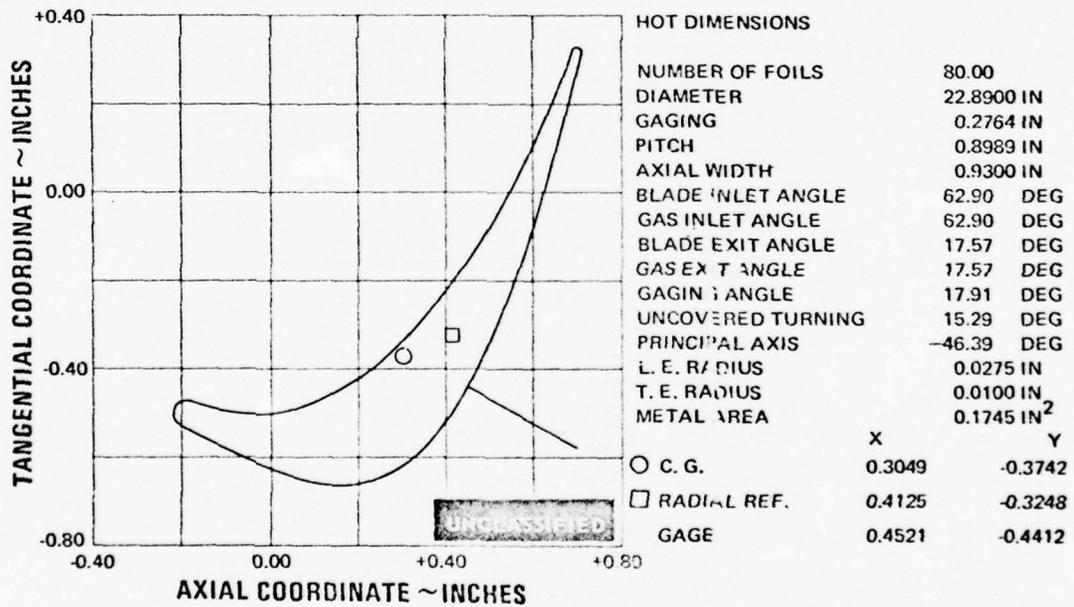


Figure 127 Recambered Second Vane, Tip Defining Section (GG)

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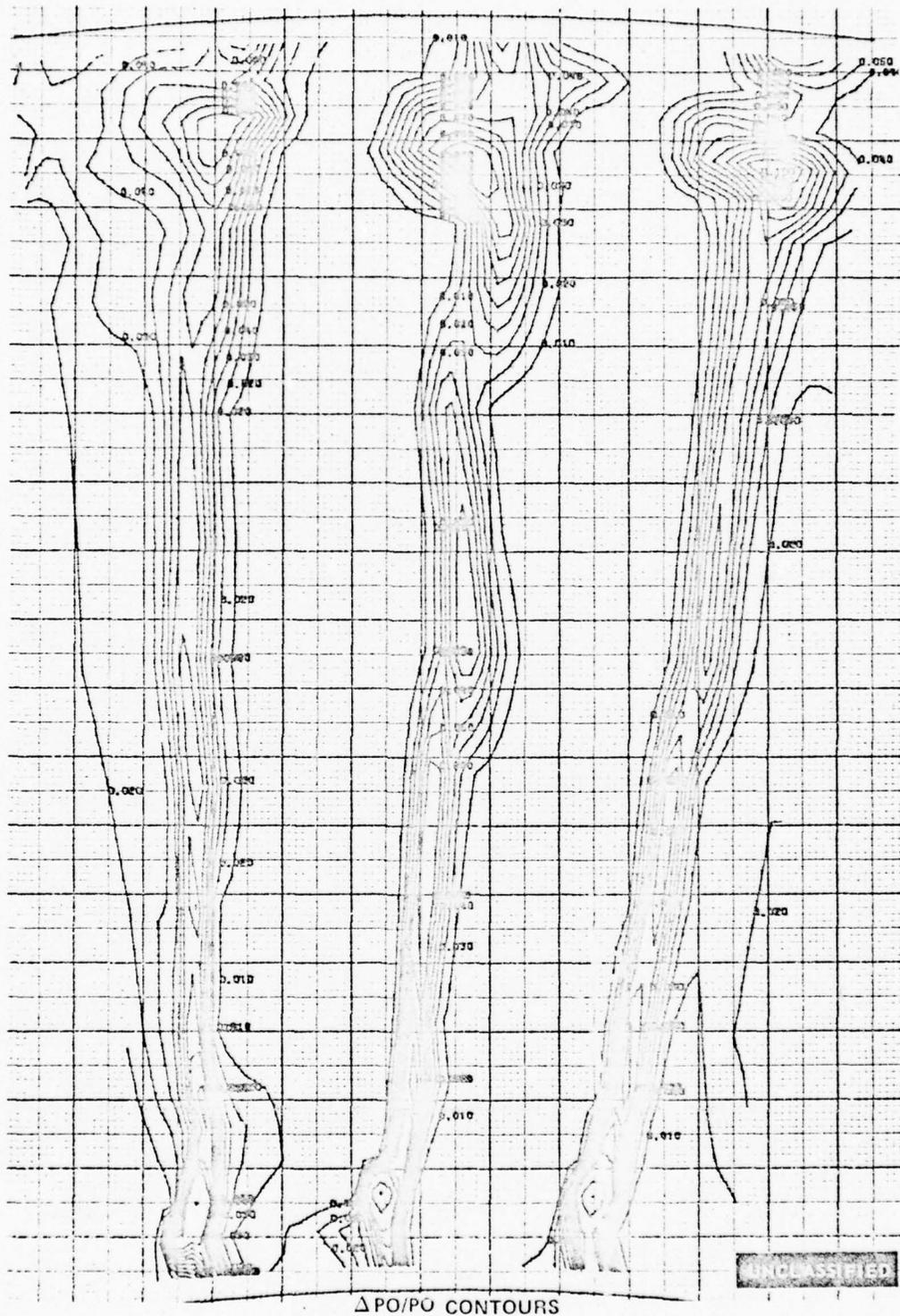
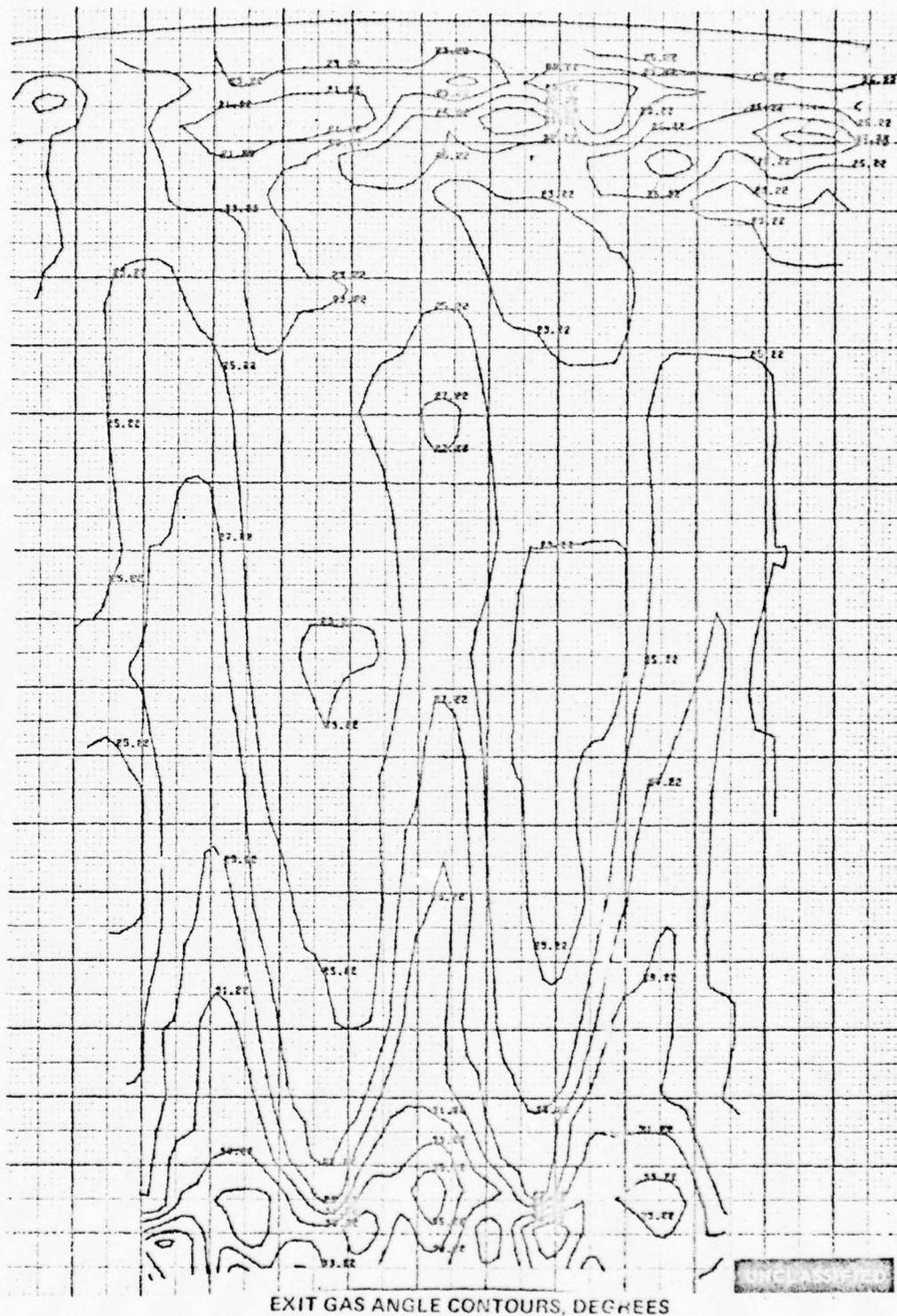


Figure 128 Pressure Loss Contours, Second Vane - Screen Installed, Three Flow Passages, Midspan Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

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EXIT GAS ANGLE CONTOURS, DEGREES

Figure 129 Exit Gas Angle Contours, Second Vane - Screen Installed. Three Flow Passages, Midspan Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

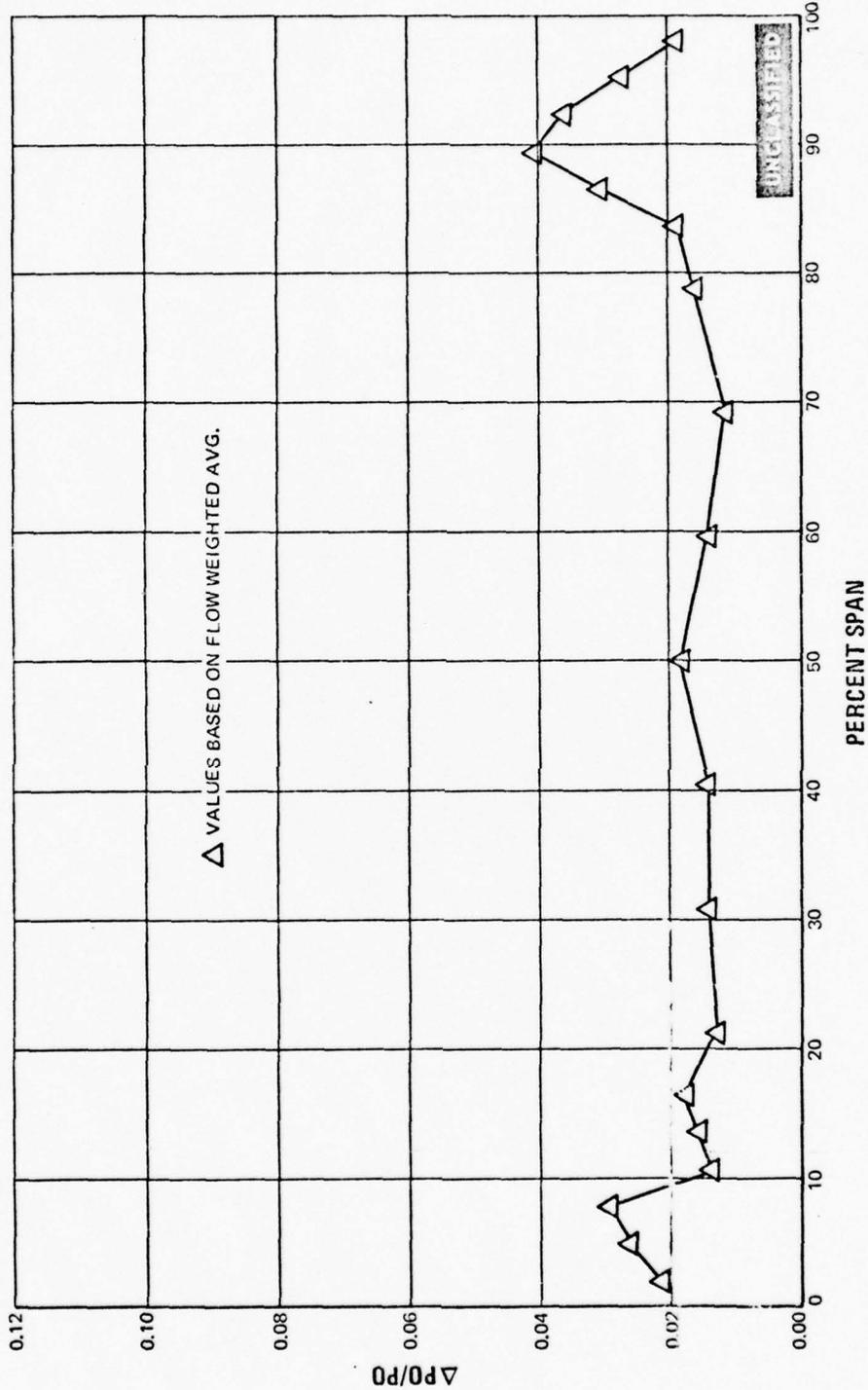


Figure 130 Spanwise Pressure Loss Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide  
Vaness and Optimum Boundary Layer Bleeds

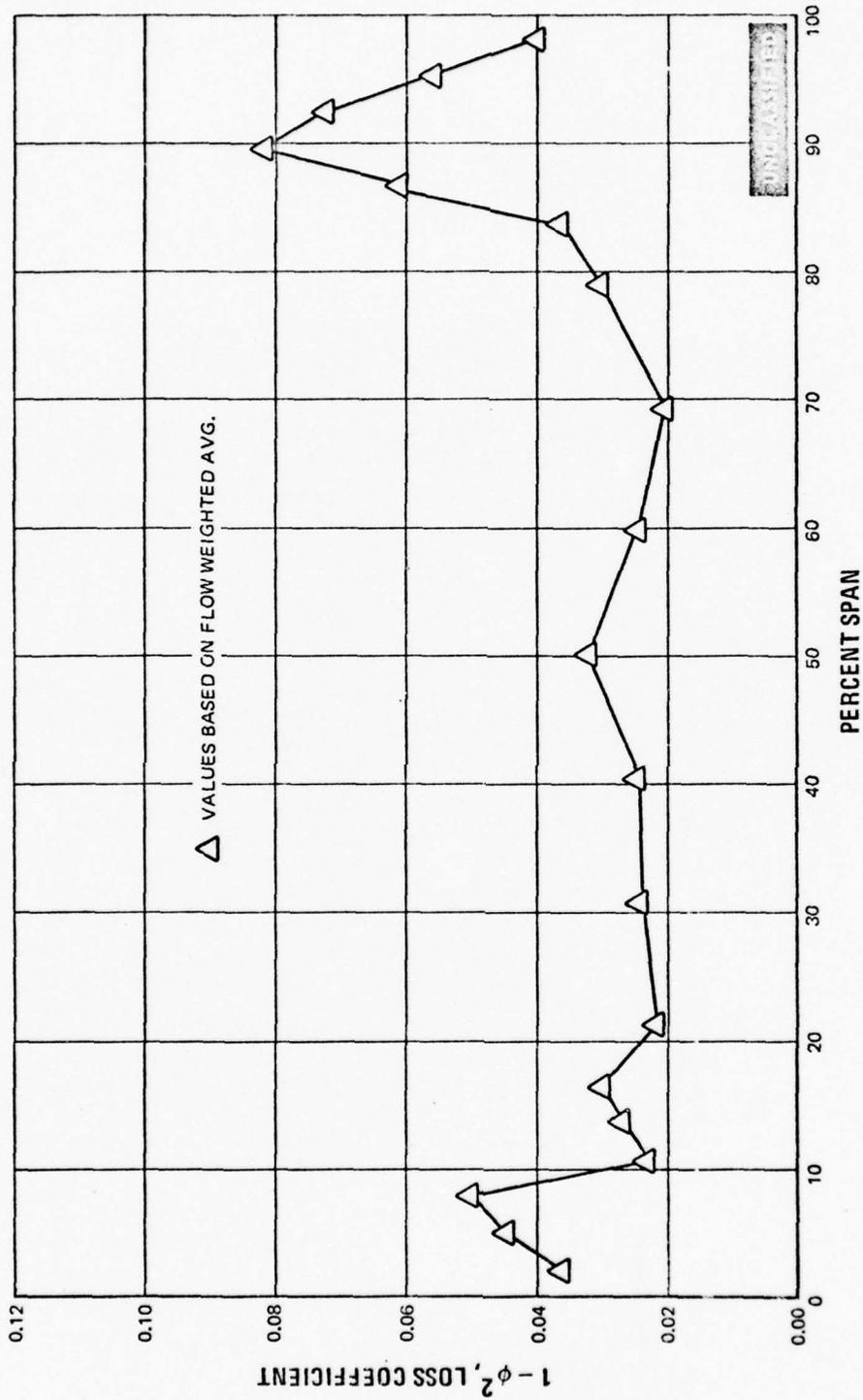


Figure 131 Spanwise Loss Coefficient, Second Vane - Screen Installed, Midspan Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

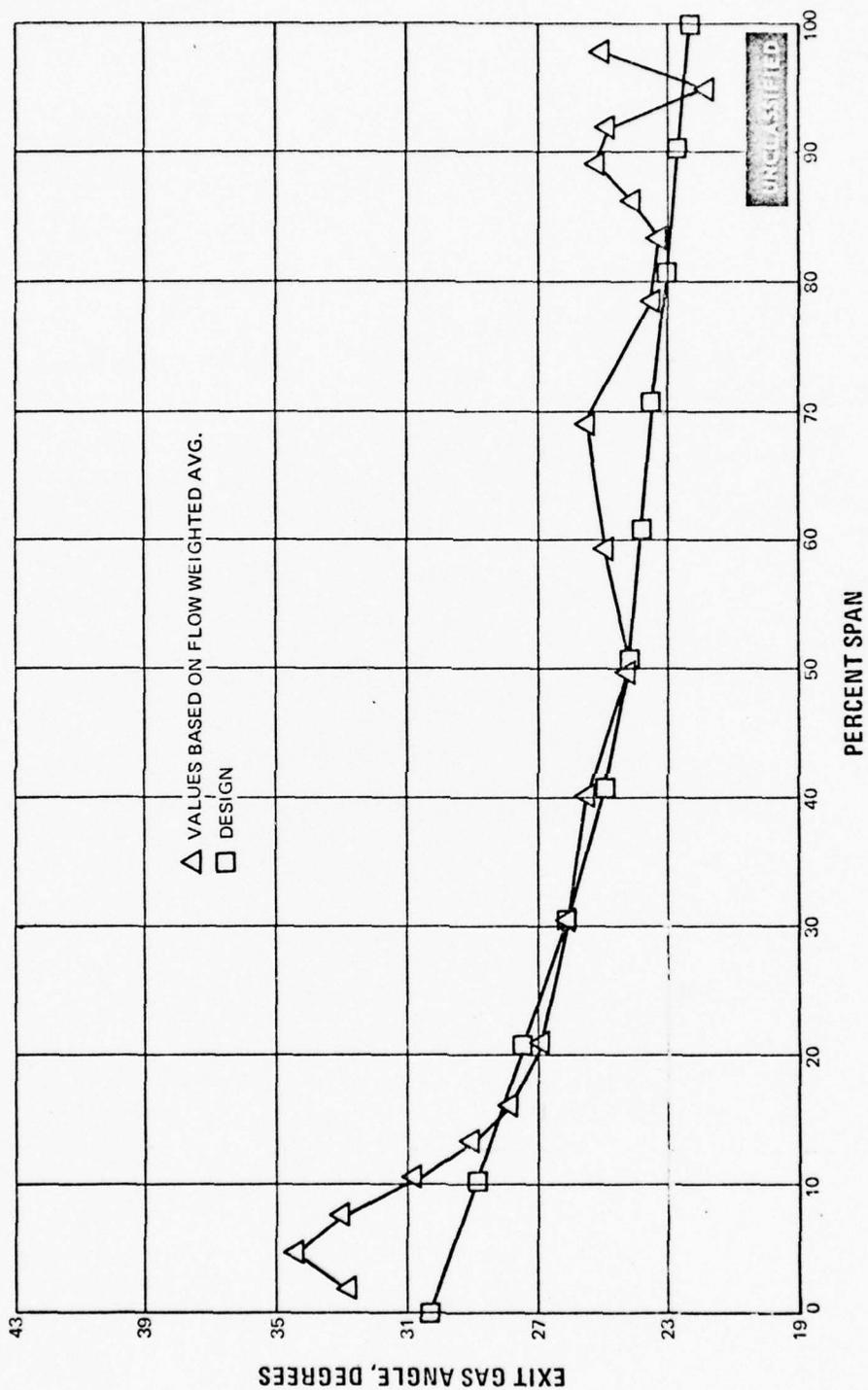


Figure 132 Spanwise Exit Gas Angle Distribution, Second Vane - Screen Installed, Midspan  
Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide  
Vaness and Optimum Boundary Layer Bleeds

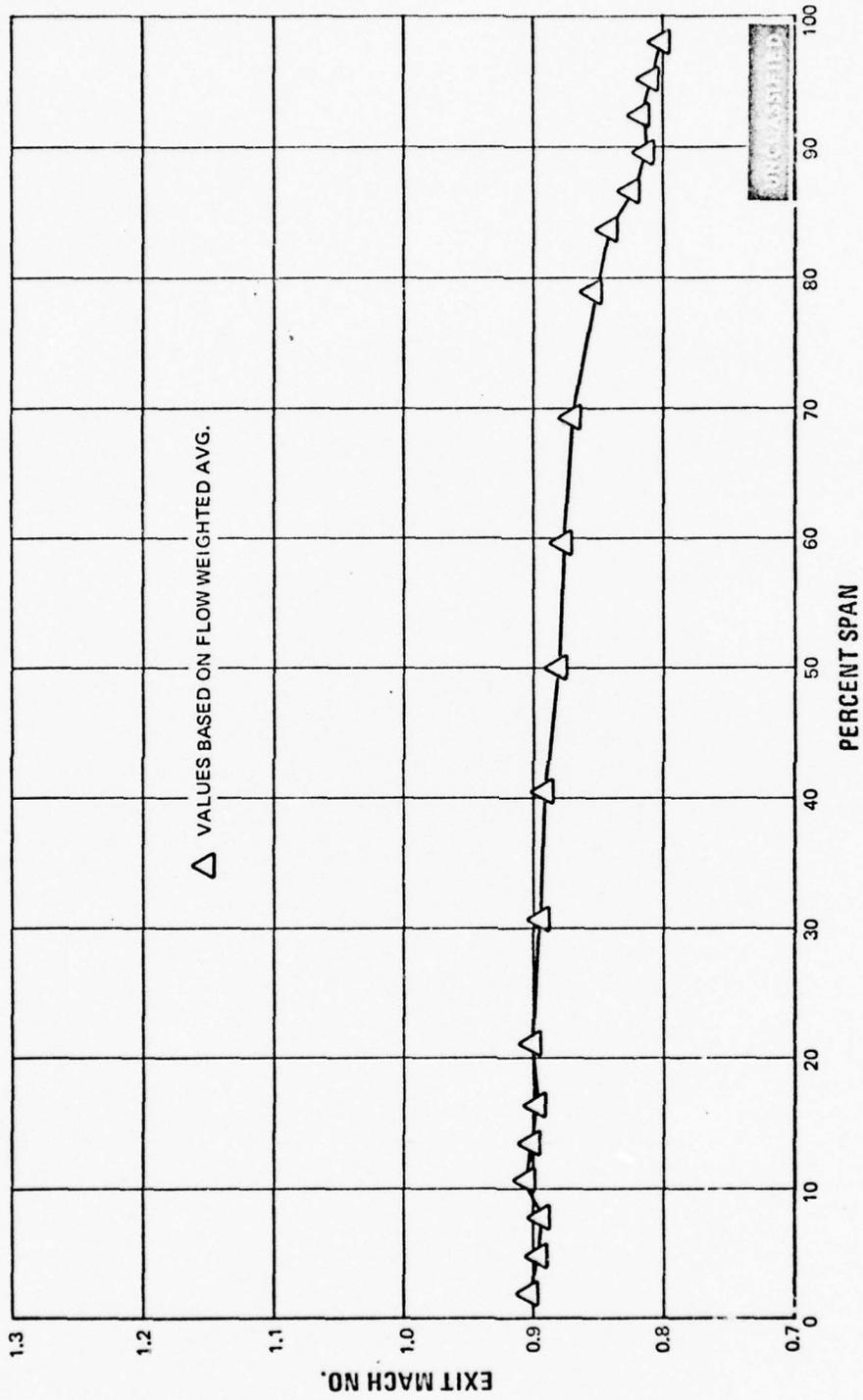


Figure 133 Spanwise Exit Mach Number Distribution, Second Vane - Screen Installed, Mid-span Exit Mach No. = 0.880, Recambered Airfoils With Redesigned Inlet Guide Vanes and Optimum Boundary Layer Bleeds

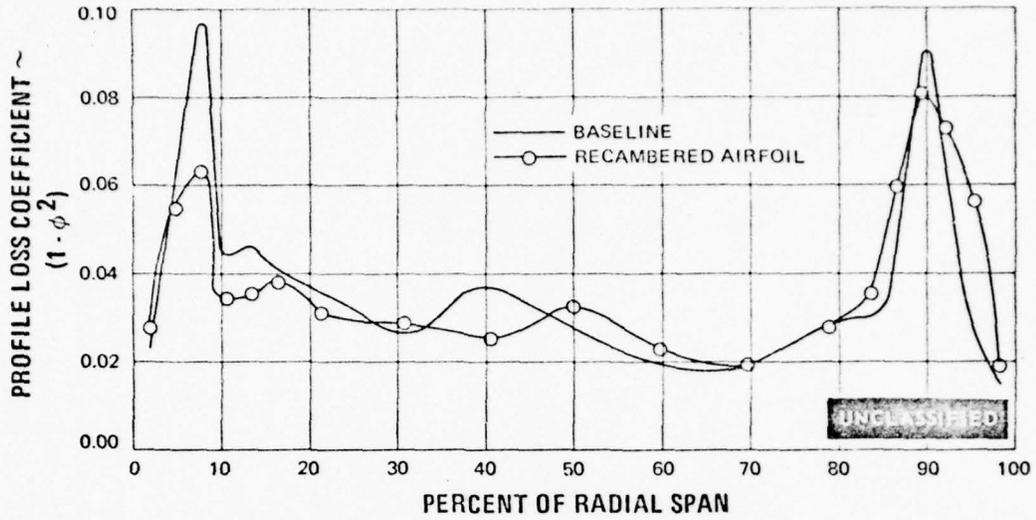


Figure 134 Comparison of Recambered Airfoil Spanwise Loss Coefficient Distribution with Baseline Values

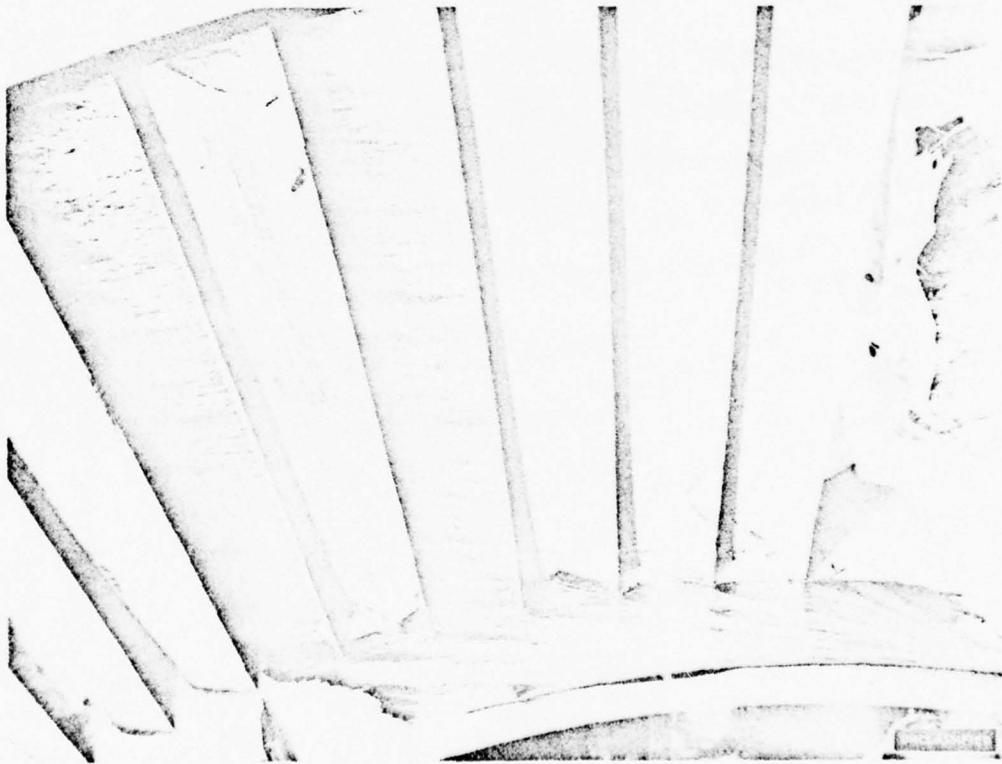


Figure 135 Oil and Graphite Flow Patterns—Second Vane Recambered Airfoils; Midspan Exit Mach No. =0.880



Figure 136 Oil and Graphite Flow Patterns—Second Vane Recambered Airfoils: Midspan Exit Mach No. =0.880

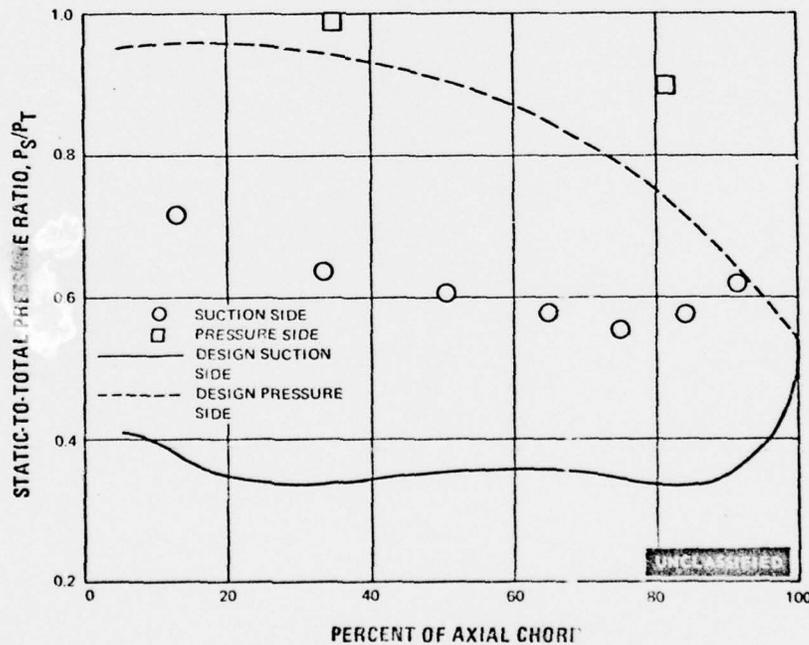


Figure 137 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Root Section

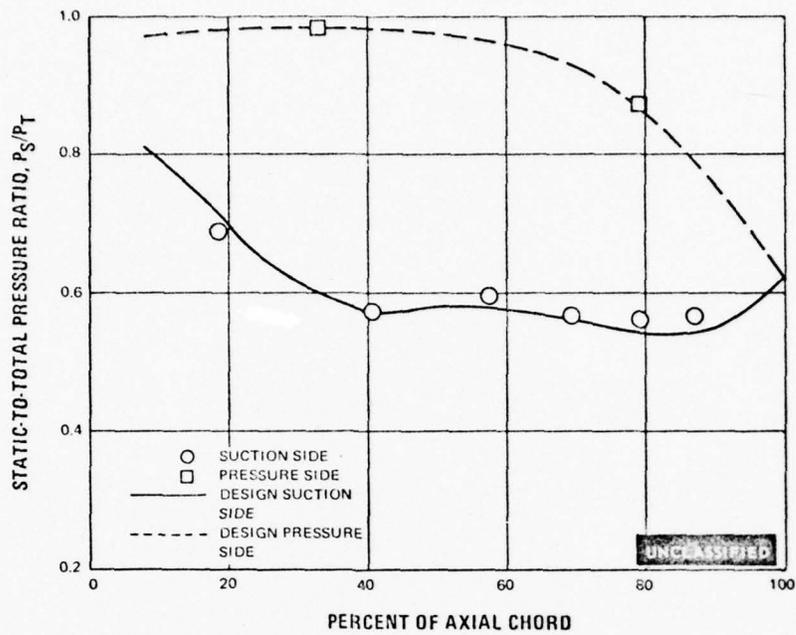


Figure 138 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Mean Section

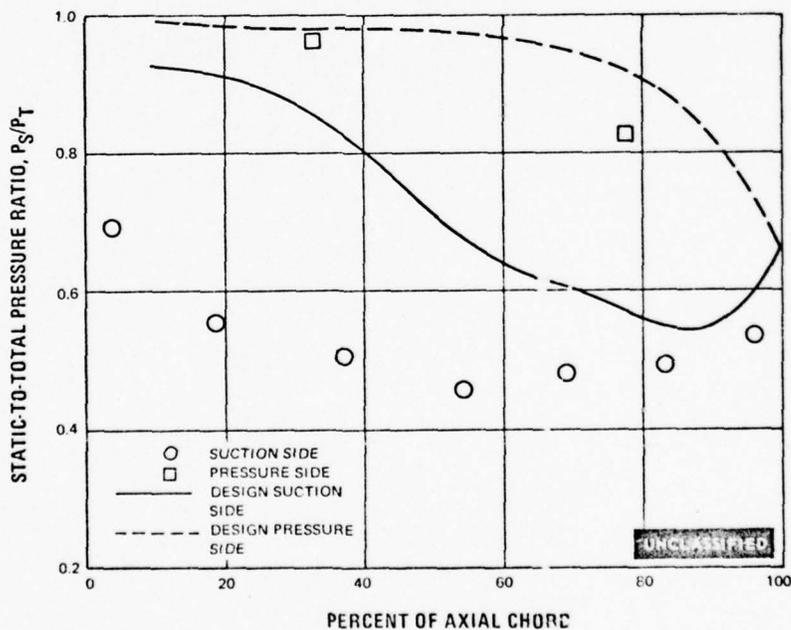


Figure 139 Static-to-Total Pressure Ratio Versus Percent of Axial Chord, Second Vane Recambered Airfoils With Redesigned Inlet Guide Vanes, Optimum Boundary Layer Bleeds and Inlet Screen—Tip Section

9. CONCLUSIONS

(U) Table XXI summarizes the measured loss coefficients for the various boundary layer control techniques, other than the flow fence/increased surface roughness test which showed no promise for future investigation. Overall loss coefficients are shown, as well as integrated values from midspan to each of the end-walls. Also, comparison plots of the average spanwise coefficients and exit gas flow angles are shown in Figures 140 and 141 for the baseline airfoil, the recontoured airfoil, end wall contouring, and recambered airfoil investigation. These plots are at the midspan exit Mach numbers of Table XXI.

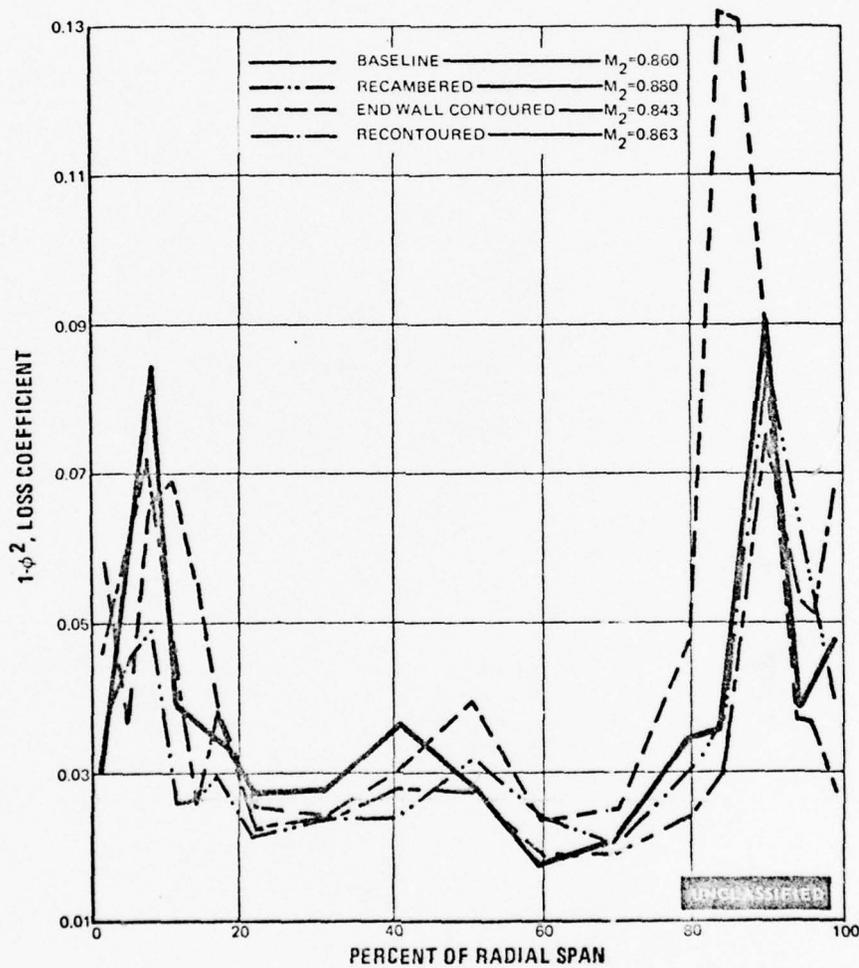


Figure 140 Comparison of Baseline Loss Coefficients With Those of Various Boundary Layer Control Methods

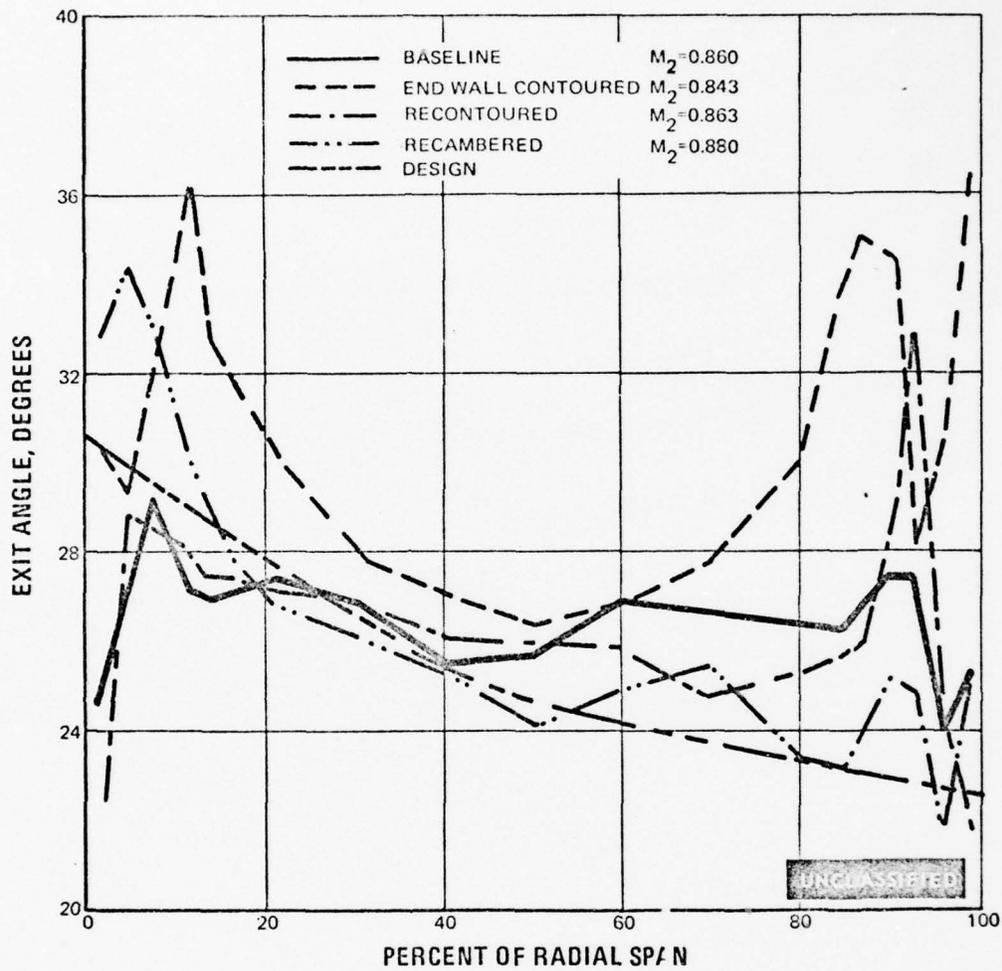


Figure 141 Comparison of Baseline Exit Flow Angles With Those of Various Boundary Layer Control Methods

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TABLE XXI

## INTEGRATED AVERAGE PROFILE LOSS COEFFICIENTS SECOND VANE CASCADE

|                     | Midspan<br>Mach No. | Overall | Loss Coefficient ( $1-\phi^2$ ) |         |
|---------------------|---------------------|---------|---------------------------------|---------|
|                     |                     |         | To I.D.                         | To O.D. |
| Baseline            | 0.860               | 0.0349  | 0.0353                          | 0.0345  |
| Recontoured Airfoil | 0.863               | 0.0336  | 0.0338                          | 0.0334  |
| End Wall Contoured  | 0.843               | 0.0428  | 0.0374                          | 0.0482  |
| Recambered Airfoil  | 0.880               | 0.0329  | 0.0286                          | 0.0372  |

(U) Based on these comparisons, it appears that the most promising method for improving turbine performance is that of local airfoil recambering. The reasons for choosing recambering are that:

- This technique was shown to have a strong effect on end losses, including significantly reducing them. It is important to decrease end-wall losses since, proportionally, the end loss per-unit-area is about 2.6 times the profile loss per-unit-area
- This is a technique which is a natural part of the airfoil design optimization if a satisfactory end-wall model is available
- This technique readily lends itself to fabrication.

(U) The other techniques showed no promise of reducing end-wall losses for the configurations that were investigated. Even though a great deal was learned about these other techniques in this program, and even though there may be a successful method of applying them, it is not now clear how this can be done within the scope of this Contract. As a result, recambering is the only practical path available.

(U) It is concluded that the greatest profit lies in the direction of recambering airfoils. Consequently, Phase IIIa will primarily consist of a variety of local recambering tests designed to give us the best qualitative and quantitative information about this method.

### 10. TEST PROCEDURE

(U) The test procedure employed during the Task IIc boundary layer control technique evaluation was identical to that of the Task IIb baseline evaluation. This procedure was described in complete detail in the Reference 3 Report.

**SECTION V**  
**MEDIUM SOLIDITY AIRFOIL EVALUATION (TASK IId)**

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## SECTION V

### MEDIUM SOLIDITY AIRFOIL EVALUATION (TASK IIc)

#### 1. OBJECTIVE

(U) The initial objective of Task IIc was to investigate two additional boundary layer control methods, other than the two methods that were investigated under Task IIb, on two different airfoils. Since the performance of the four baseline airfoils was very similar (Reference 3), Task IIc was modified so that four boundary layer control methods were applied only to the second vane (see Section IV of this report), eliminating the need for Task IIc as originally conceived. By mutual agreement with the Air Force, the work substituted for the original Task IIc was the evaluation of the performance of lower solidity and higher load coefficient airfoils designed for the same velocity triangles as the baseline airfoils of Task IIb. The performance of the first vane and first blade lower-solidity airfoils is reported in this section.

#### 2. TASK OBJECTIVE

(U) Each of the four medium solidity airfoils will be evaluated in an annular segment cascade, exactly as in Task IIb (Reference 3). As of the time of writing this interim report, work on the first vane and blade had been completed; and for these two airfoils, the task objectives were met by the following steps:

- Measurement of all important aerodynamic properties at the cascade inlet and exit planes
- Reconstruction of the entire exit plane loss distribution
- Reconstruction of the entire exit plane flow pattern
- Measurement of the airfoil surface static pressure distributions at three radial locations
- Careful analysis of all data and visual clues.

#### 3. AIRFOIL SECTION AND FACILITY DESIGN

(U) The medium-reaction, medium-solidity airfoils were designed to the same turbine velocity diagrams as the normal solidity airfoils. These were reported in the Reference 1 Report. A summary of the pertinent design values, the airfoil elevations, gaging distribution, airfoil sections, predicted surface pressure distribution, and airfoil radius of curvature for each of the four airfoils was presented at five spanwise locations in the Reference 3 Report. The four airfoils are the first and second vanes, and the first and second blades. The fabrication coordinates of each airfoil were also tabulated in the Reference 3 Report, including the airfoil angles, airfoil areas, axial chords and uncovered turnings.

(U) The test section design for each of the four medium-solidity airfoils is as close as possible to the normal solidity cascades. Since the normal solidity cascade exhausted to atmosphere and the medium solidity cascade rig was connected to the laboratory exhaust system, differences in the exit configurations of these cascades resulted. The inlet guide vane designs were identical for both rigs. The designs of the inlet guide vanes were presented in the Reference 2 Report.

(U) Static pressure instrumentation was installed in order to determine the static pressure distributions on the airfoils, and over both the test airfoil inlet and exit end walls in the medium-solidity cascade rig. The static pressure instrumentation on the airfoils was located at the mean section and at a section 0.1 inch from the outer and inner end-walls. These sections are shown in Figure 142, and the axial chord locations of the pressure taps are listed in Tables XXII through XXV for the four configurations tested. Great care was taken to preserve the contour and smoothness of the suction side of each instrumented airfoil. To this end, all hypodermic tube leads were placed in grooves on the pressure surface, and pressure tap holes were then drilled into these tubes from the suction surface (see Figure 143). The instrumented airfoil was located next to the center channel in each of the four configurations.

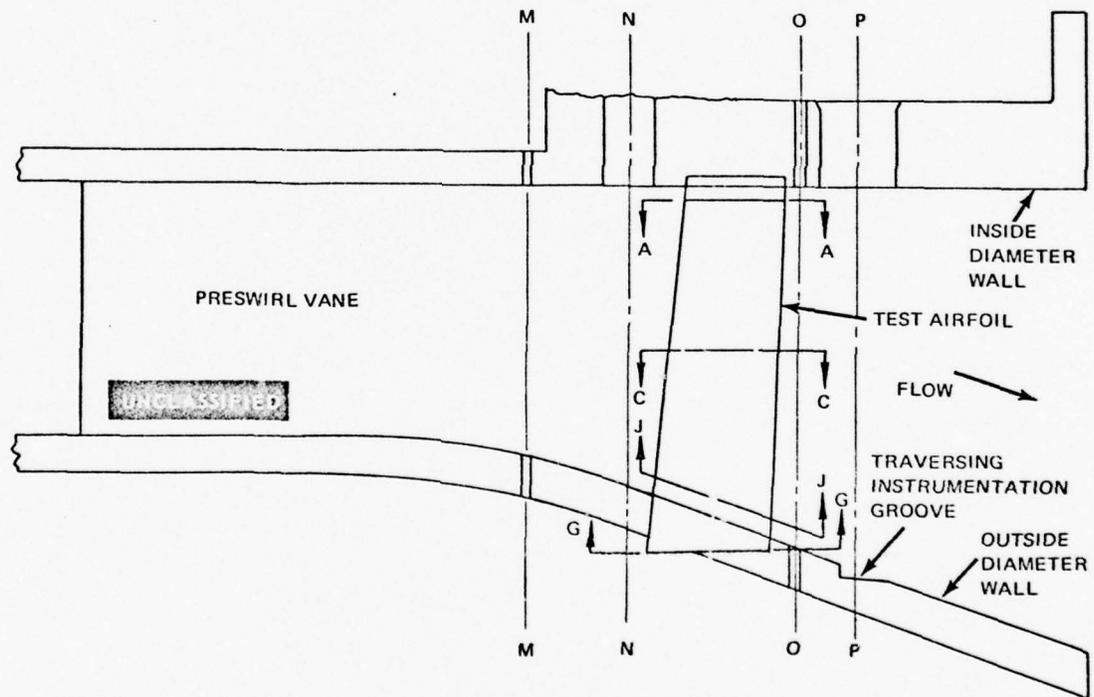


Figure 142 Medium Solidity Annular Segment Cascade - Flowpath Cross-Section

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TABLE XXII

AIRFOIL STATIC PRESSURE INSTRUMENTATION  
MEDIUM SOLIDITY

| Section                | Airfoil Side | Axial Length<br>From L. E. | X/bx  |
|------------------------|--------------|----------------------------|-------|
| Root<br>Section<br>A-A | Suction      | 0.044                      | 0.056 |
|                        |              | 0.128                      | 0.165 |
|                        |              | 0.211                      | 0.273 |
|                        |              | 0.295                      | 0.382 |
|                        |              | 0.379                      | 0.490 |
|                        |              | 0.462                      | 0.598 |
|                        |              | 0.546                      | 0.707 |
|                        |              | 0.630                      | 0.816 |
|                        | Pressure     | 0.520                      | 0.674 |
|                        |              | 0.265                      | 0.344 |
| Mean<br>Section<br>C-C | Suction      | 0.084                      | 0.100 |
|                        |              | 0.251                      | 0.299 |
|                        |              | 0.335                      | 0.400 |
|                        |              | 0.419                      | 0.500 |
|                        |              | 0.502                      | 0.599 |
|                        |              | 0.586                      | 0.700 |
|                        |              | 0.670                      | 0.799 |
|                        |              | 0.754                      | 0.899 |
|                        | Pressure     | 0.703                      | 0.840 |
|                        |              |                            |       |
| Tip<br>Section<br>G-G  | Suction      | 0.100                      | 0.110 |
|                        |              | 0.309                      | 0.340 |
|                        |              | 0.499                      | 0.548 |
|                        |              | 0.574                      | 0.631 |
|                        |              | 0.655                      | 0.720 |
|                        |              | 0.710                      | 0.780 |
|                        |              | 0.792                      | 0.870 |
|                        |              | Pressure                   | 0.681 |
|                        | 0.390        |                            | 0.429 |

NOTE: Tip section taps are actually located parallel to wall on section J-J shown in Figure 142.

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TABLE XXIII  
 AIRFOIL STATIC PRESSURE INSTRUMENTATION  
 MEDIUM SOLIDITY  
 FIRST STAGE BLADE

| Section        | Airfoil Side | Axial Length<br>From L.E. | X/bx  |
|----------------|--------------|---------------------------|-------|
| Root           | Suction      |                           |       |
| Section<br>A-A |              | 0.074                     | 0.124 |
|                |              | 0.276                     | 0.464 |
|                |              | 0.405                     | 0.681 |
|                |              | 0.476                     | 0.800 |
| Mean           | Suction      |                           |       |
| Section<br>C-C |              | 0.060                     | 0.105 |
|                |              | 0.150                     | 0.264 |
|                |              | 0.239                     | 0.421 |
|                |              | 0.359                     | 0.632 |
|                |              | 0.419                     | 0.737 |
| Tip            | Suction      |                           |       |
| Section<br>G-G |              | 0.108                     | 0.201 |
|                |              | 0.215                     | 0.400 |
|                |              | 0.323                     | 0.600 |
|                |              | 0.377                     | 0.700 |
|                |              | 0.430                     | 0.800 |

NOTE: Tip section taps are actually located parallel to wall on section J-J shown on Figure 142.

TABLE XXIV

AIRFOIL STATIC PRESSURE INSTRUMENTATION  
MEDIUM SOLIDITY  
SECOND STAGE VANE

| Section                        | Airfoil Side | Axial Length<br>From L.E. | X/bx  |
|--------------------------------|--------------|---------------------------|-------|
| Root<br><br>Section<br><br>A-A | Suction      | 0.083                     | 0.990 |
|                                |              | 0.167                     | 0.199 |
|                                |              | 0.250                     | 0.298 |
|                                |              | 0.334                     | 0.398 |
|                                |              | 0.418                     | 0.496 |
|                                |              | 0.510                     | 0.608 |
|                                |              | 0.585                     | 0.696 |
|                                |              | 0.668                     | 0.795 |
|                                | Pressure     | 0.561                     | 0.669 |
|                                |              | 0.191                     | 0.227 |
| Mean<br><br>Section<br><br>C-C | Suction      | 0.088                     | 0.100 |
|                                |              | 0.176                     | 0.200 |
|                                |              | 0.264                     | 0.300 |
|                                |              | 0.371                     | 0.421 |
|                                |              | 0.440                     | 0.500 |
|                                |              | 0.528                     | 0.600 |
|                                |              | 0.616                     | 0.700 |
|                                |              | 0.705                     | 0.800 |
|                                | Pressure     | 0.620                     | 0.704 |
|                                |              | 0.179                     | 0.203 |
| Tip<br><br>Section<br><br>G-G  | Suction      | 0.256                     | 0.275 |
|                                |              | 0.473                     | 0.509 |
|                                |              | 0.544                     | 0.585 |
|                                |              | 0.618                     | 0.665 |
|                                |              | 0.674                     | 0.725 |
|                                |              | Pressure                  | 0.762 |
|                                | 0.759        |                           | 0.816 |

NOTE: O. D. taps are actually located parallel to wall on section J-J shown on Figure 142.

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TABLE XXV  
 AIRFOIL STATIC PRESSURE INSTRUMENTATION  
 MEDIUM SOLIDITY  
 SECOND STAGE BLADE

| Section | Airfoil Side | Axial Length<br>From L.E. | X/bx  |
|---------|--------------|---------------------------|-------|
| Root    | Suction      |                           |       |
| Section |              | 0.081                     | 0.125 |
|         |              | 0.200                     | 0.308 |
| A-A     |              | 0.342                     | 0.528 |
|         |              | 0.530                     | 0.817 |
| Mean    | Suction      |                           |       |
| Section |              | 0.058                     | 0.100 |
|         |              | 0.174                     | 0.300 |
| C-C     |              | 0.289                     | 0.500 |
|         |              | 0.405                     | 0.700 |
| Tip     | Suction      |                           |       |
| Section |              | 0.100                     | 0.200 |
|         |              | 0.200                     | 0.400 |
| G-G     |              | 0.300                     | 0.600 |
|         |              | 0.400                     | 0.800 |

NOTE: Tip section taps are actually located parallel to wall on section J-J shown on Figure 142.



Figure 143 Typical Installation of Airfoil Surface Static Instrumentation

(U) The static pressure instrumentation in the test airfoil exit plane was located on both end walls, 0.1 inch axially downstream from the test airfoils. These taps are located at section 0-0 on Figures 142 and 144. A total of fifteen taps for each end-wall were evenly distributed circumferentially so that two complete channels were surveyed. The static pressure instrumentation for the inlet plane was located downstream of the preswirl vanes at section M-M (Figures 142 and 144). Three taps were placed on each end-wall at the centers of the three channels.

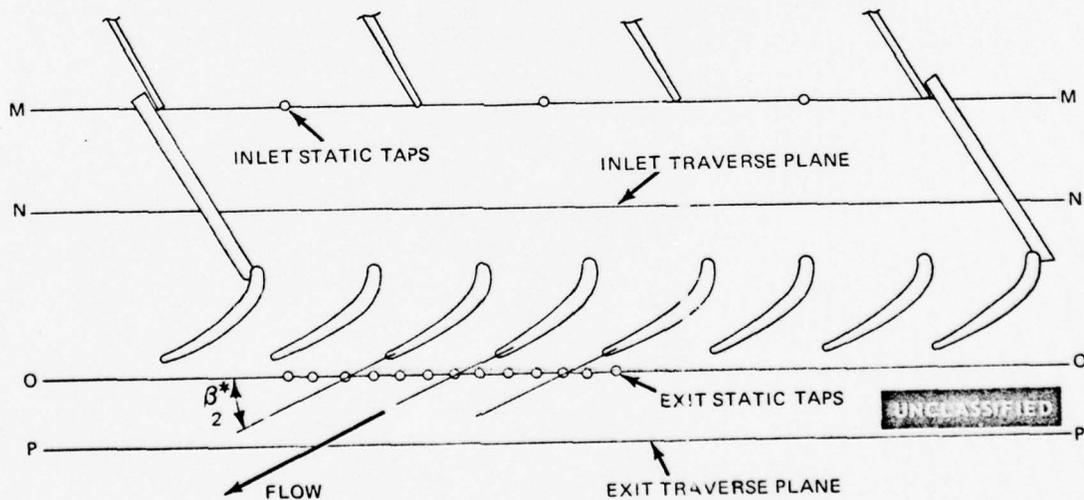


Figure 144 Medium Solidity Annular Segment Cascade -- Unfolded View of Test Section

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(U) Four inlet static pressure taps and four total temperature probes were located before and after the inlet plenum screen. Four pressure taps, located in the exit plenum, measured the exit static pressure. A study of these plenum configurations showed the static pressures were equal to the total pressure; therefore, the static taps were used for plenum total pressure readings.

(U) The axial locations of the traverse planes in the medium solidity cascade rig are shown in Figures 142 and 144. Flow quantities necessary for evaluation of the airfoil performance are measured at both these inlet and exit planes. The traversing mechanism moved the probe in circumferential arcs of constant angular extent, and across the flow from the center three channels. The total pressure and gas angle was traversed at nineteen radial locations distributed symmetrically spanwise about the mean. The percents of span for these locations are as follows: 0, 2, 5, 8, 11, 14, 17, 22, 30, 50, 70, 78, 83, 86, 89, 92, 95, 98 and 100. In order to define the end-wall regions more accurately, more traverses were taken in the end regions.

(U) The probe used to measure the total pressure and flow direction was an extended tip yaw angle-seeking cobra probe. This probe has low blockage, operates well at high Mach numbers, and is ideally suited for the traversing mechanism used in this rig. A front view of the cobra probe is shown in Figure 145.



Figure 145 Probes Used in Medium Solidity Annular Cascade - From Left to Right: 1.5 Inch Minimum Blockage "Cobra" Probe ( $P_{TOTAL} + A/A$ ), "Knee" Probe (Pitch Angle), "Banjo" Probe ( $P_{STATIC} + A/A$ )

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(U) The slope of the outer wall gives a good indication that significant radial velocities will exist in all the cascade configurations, and stream line calculations using the Turbine Streamline Program proved this to be the case. Therefore, the cobra probe required calibration for pitch angle incidence. A typical example of this pitch angle error is shown in Figure 146. The pitch angle is that angle measured from the shaft axis of the probe, and is equal to the sum of  $90^\circ$  and the arc tangent of the radial velocity component divided by the stream line velocity or  $\left[90^\circ + \tan^{-1}\left(\frac{C_r}{C}\right)\right]$ .

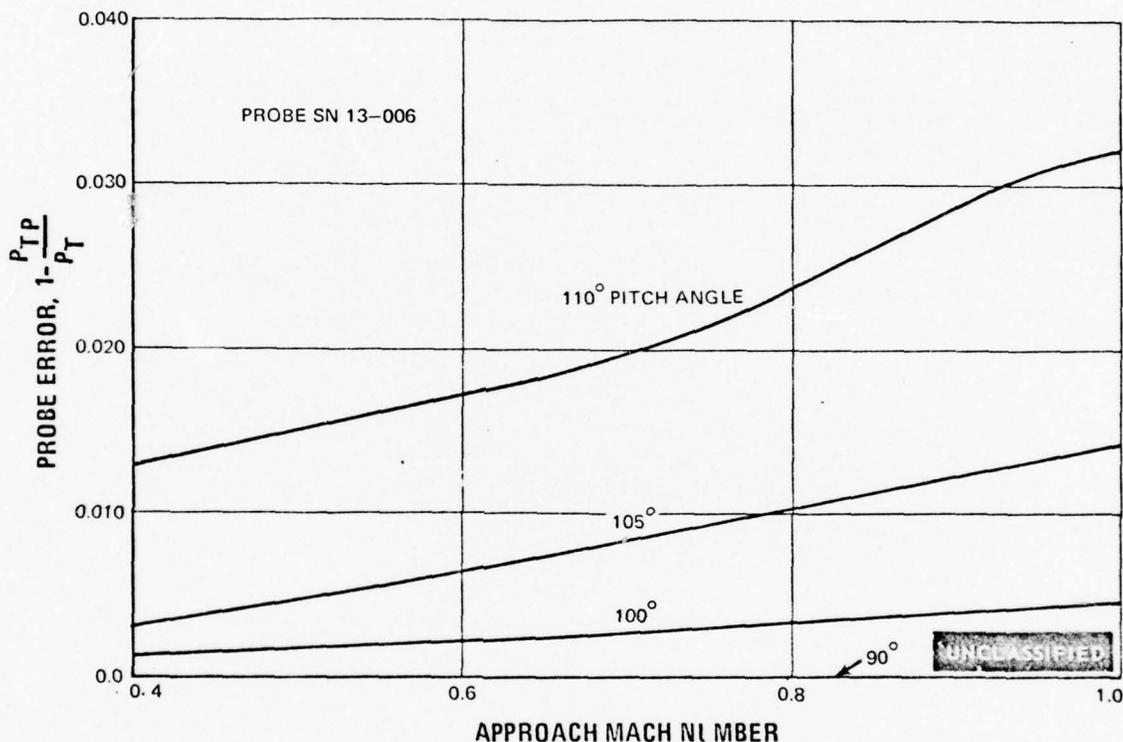


Figure 146 Medium Solidity Cascade Probe Calibration

(U) For the purpose of correcting the total pressure measurements of the cobra probe, the actual pitch angle was measured at the test airfoil exit plane with a pitch angle probe. A picture of this probe is shown in Figure 145. Each cascade test airfoil exit plane was calibrated and a typical result is shown in Figure 147. Here, the experimental results for the second blade are compared with the analytical prediction. At the test airfoil inlet plane, general agreement with the predicted values made it reasonable to use these values when analyzing the performance of the inlet guide vanes and calculating the test airfoil inlet total pressure profile.

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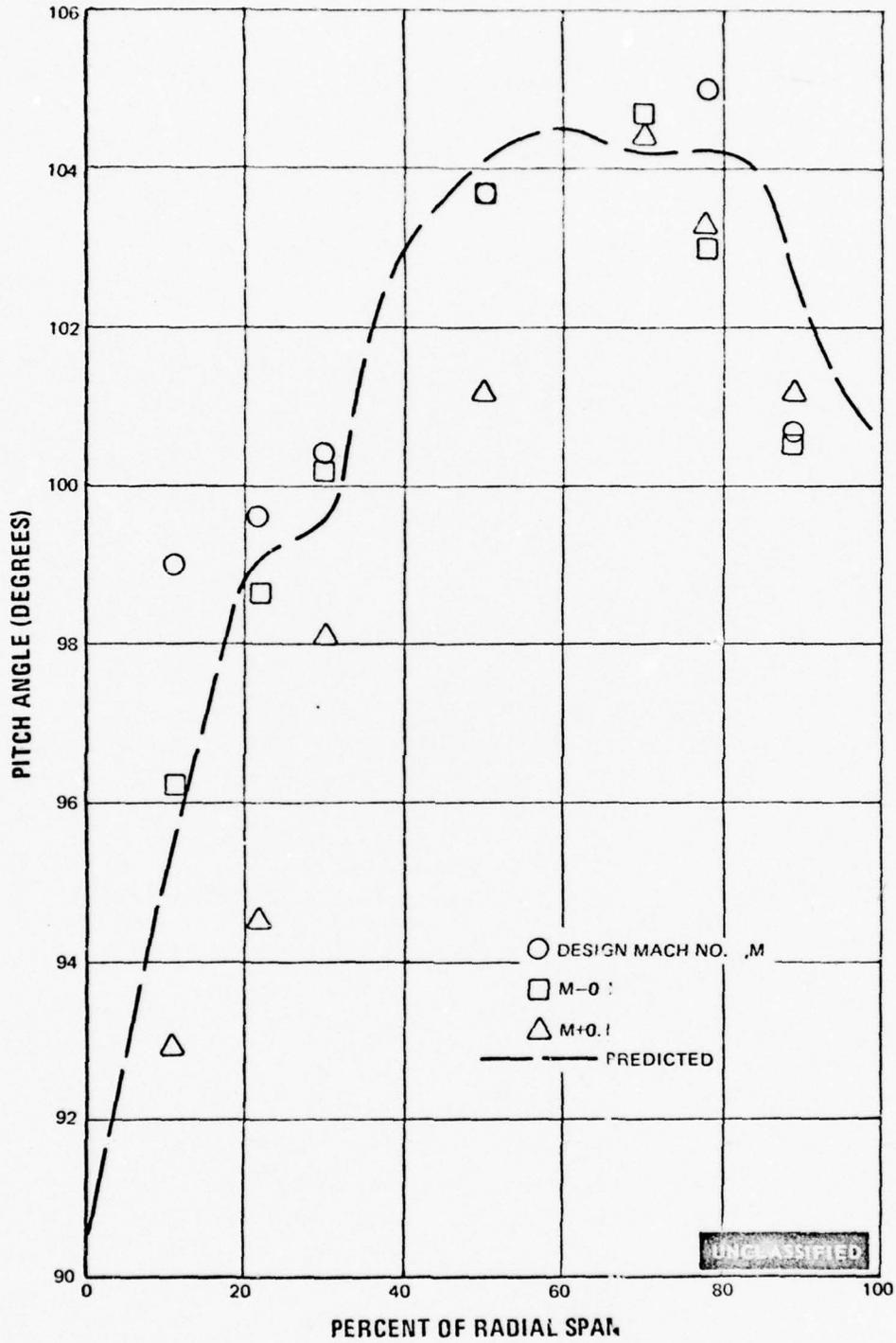


Figure 147 Medium Solidity Second Blade Pitch Angle

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(U) Prior to initiating test on the first vane cascade, a banjo probe was used to measure the static pressures at the exit plane. This probe is also shown in Figure 145. Although this probe is difficult to use for measuring static pressure at high design point Mach numbers, it did indicate a smooth static pressure profile at a mean section exit Mach number of 0.6. Experience with previous testing also showed this smooth variation of static pressure at the exit plane.

## 4. DISCUSSION

(U) The testing and analysis of the data on the medium-reaction, medium-solidity first vane and first blade has been completed. Initial testing of the second vane and second blade has been done, but the data analysis was not completed at the time of writing of this interim report.

(U) For the first vane and first blade, data were taken at the design Mach numbers and at Mach numbers 0.1 below and above the design value, while holding the design Reynolds Number constant. Also, data were taken for the first vane cascade at Reynolds Numbers 50 and 75 percent below the design Reynolds Number and 50 percent above the design Reynolds Number while holding the Mach Number constant at the design value. Except for the 75 percent below design Reynolds Number point, Reynolds Number data were also taken for the first blade. The purpose of taking the test data in this manner was to isolate the Mach number and Reynolds Number effects.

(U) The inlet guide vanes have been calibrated for all four airfoil cascades. Their performance was determined by traversing the inlet to the test airfoils. The measured total pressure loss contours (Figures 148 through 151), the out-of-wake average spanwise loss distribution with probe corrections (Figures 152 through 155) and the inlet guide vane average spanwise exit flow angle (Figures 156 through 159) are presented. The out-of-wake total pressure levels were calculated for the test airfoil inlet conditions since the test airfoil flow channel was not in the path of the inlet guide vane wakes.

(U) Analysis of the inlet guide vane data indicates that the first vane and first blade test airfoils had acceptable inlet pressure loss contours (Figures 148 and 149). Exit gas flow angles from these two guide vanes were also satisfactory (Figures 156 and 157), the incidence on the test airfoils being small over the major portion of the airfoil span. The usual passage secondary flow causes the overturning at the inlet guide vane walls noted in these figures. The second vane inlet guide vane pressure loss contours, however, show excessively large losses and incidence ( $+5^\circ$ ), indicating that the inlet guide vanes must be corrected before further testing can be justified (Figures 150 and 158). This did not come as a surprise since, as noted in the Reference 3 Report, the normal solidity second vane inlet guide vane of the same design (Task IIb) had to be redesigned for the (Task IIc) boundary layer control evaluation (see Section IV of this Report). This information became known after the guide vanes were fabricated for this medium-solidity test. The second blade cascade also has a drastic positive incidence in the upper half of the span. This inlet guide vane must also be corrected before additional tests are made.

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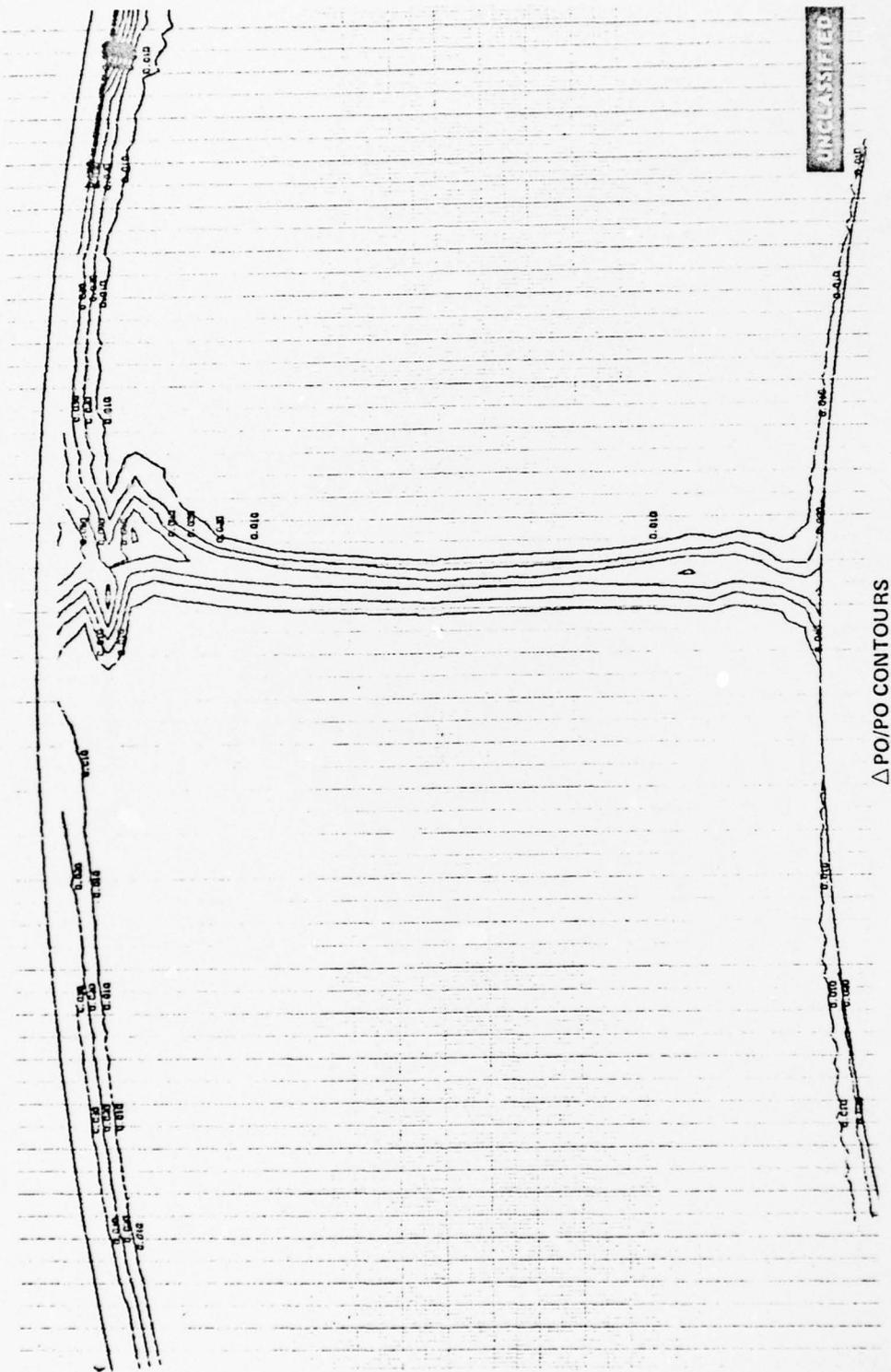


Figure 148 Inlet Guide Vane Pressure Loss Contours, First Vane Medium Solidity  
Cascade—Midspan Exit Test Airfoil Mach No. = 0.835

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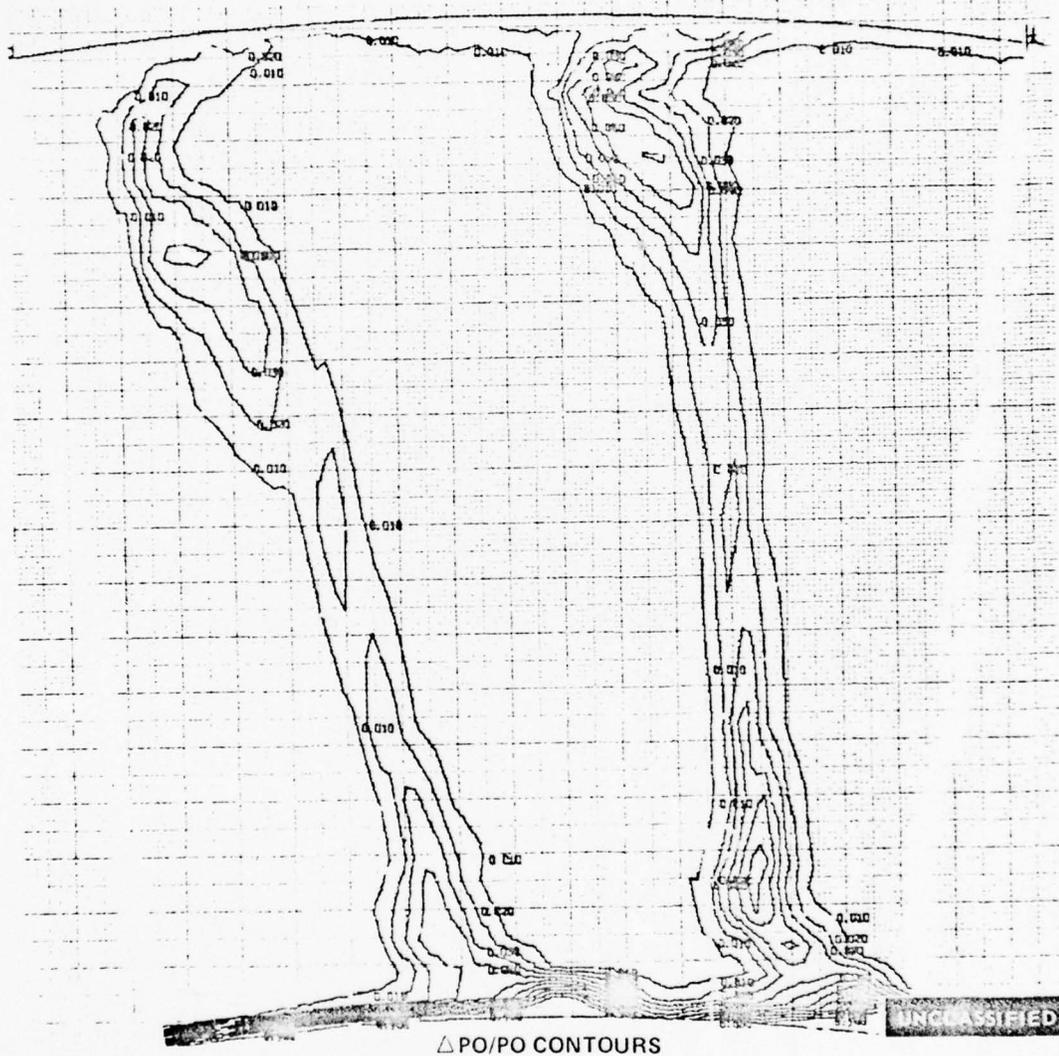


Figure 149 Inlet Guide Vane Pressure Loss Contours, First Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. = 0.775

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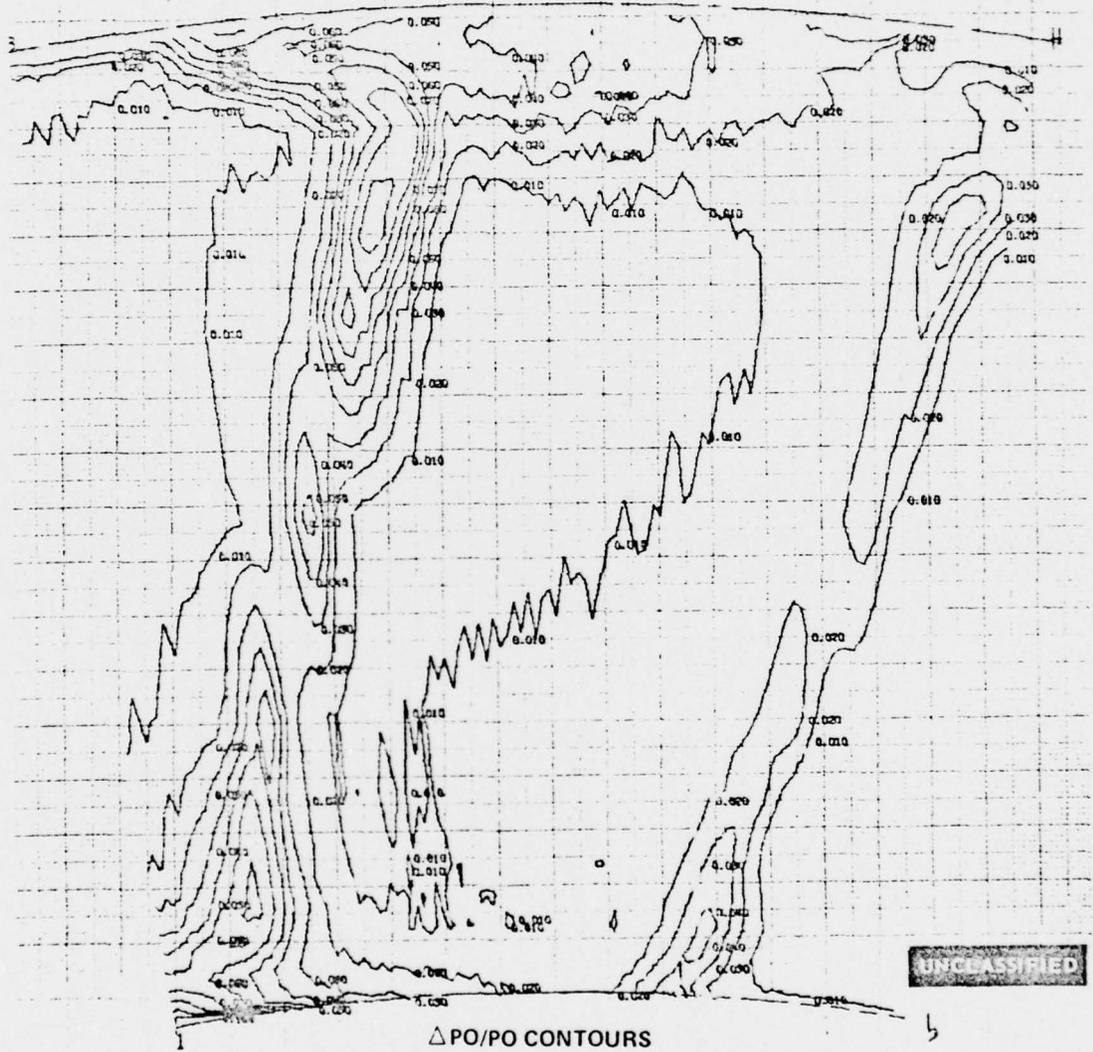


Figure 150 Inlet Guide Vane Pressure Loss Contours, Second Vane Medium Solidity Cascade-Midspan Exit Test Airfoil Mach No. = 0.860

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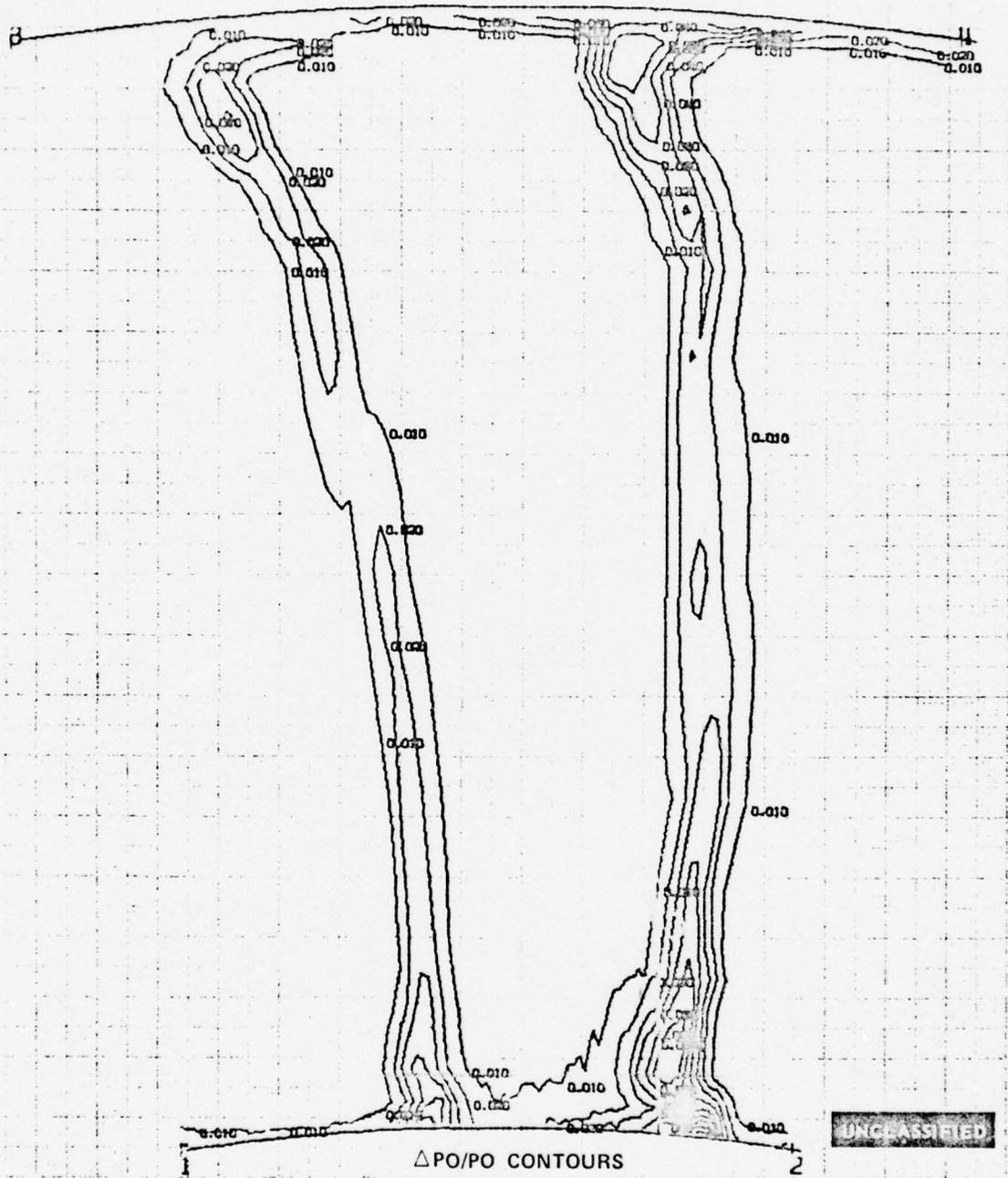


Figure 151 Inlet Guide Vane Pressure Loss Contours, Second Blade Medium Solidity Cascade-Midspan Exit Test Airfoil Mach No. = 0.918

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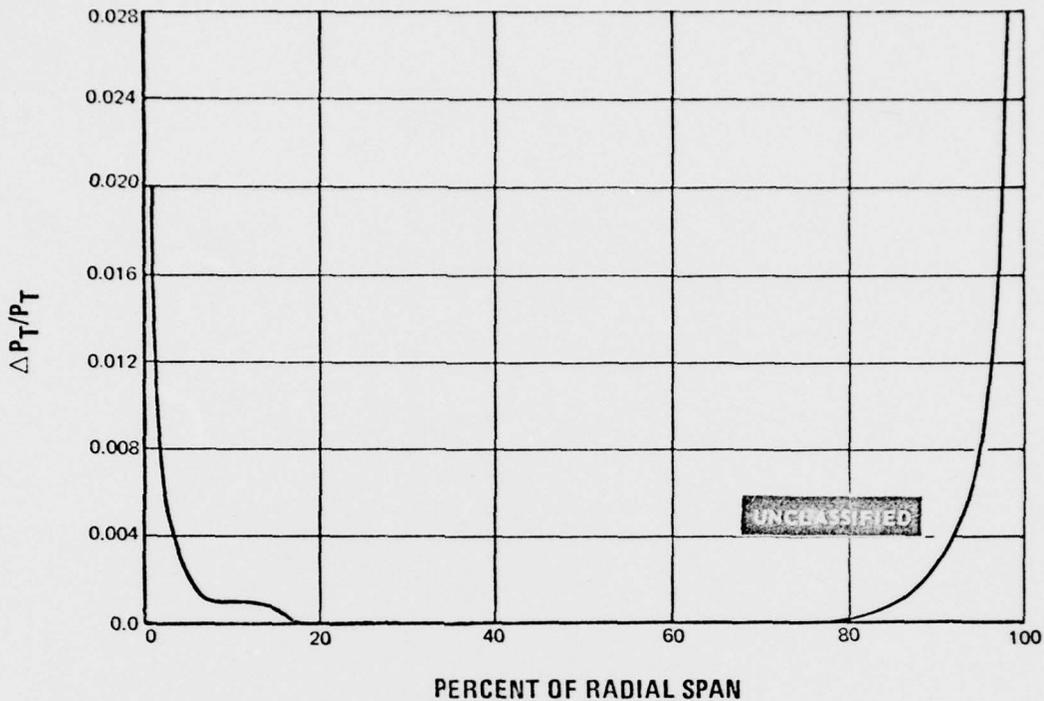


Figure 152 Inlet Guide Vane Spanwise Pressure Loss Distribution, First Vane Medium Solidity Cascade--Midspan Exit Test Airfoil Mach No. = 0.835

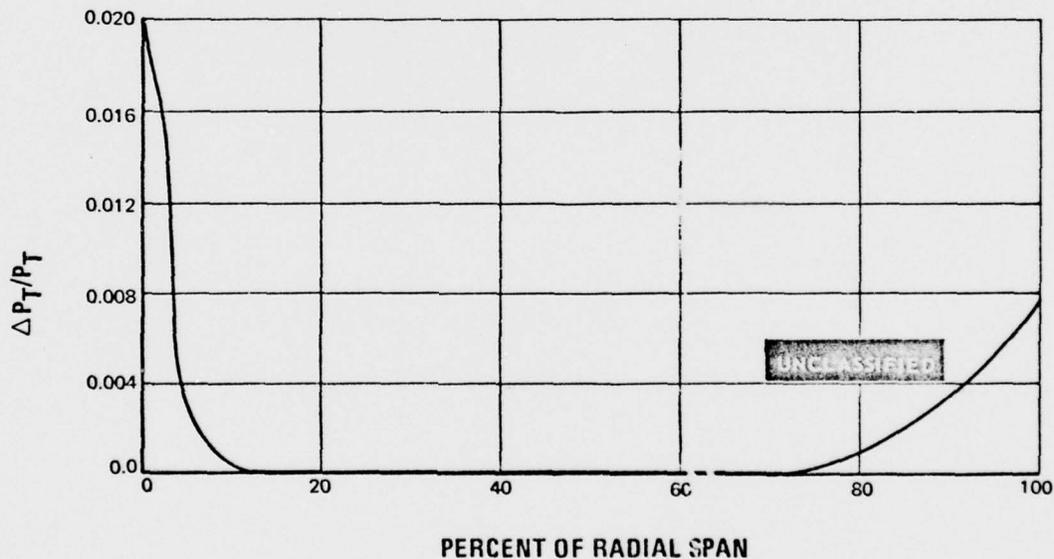


Figure 153 Inlet Guide Vane Spanwise Pressure Loss Distribution, First Blade Medium Solidity Cascade--Midspan Exit Test Airfoil Mach No. = 0.775

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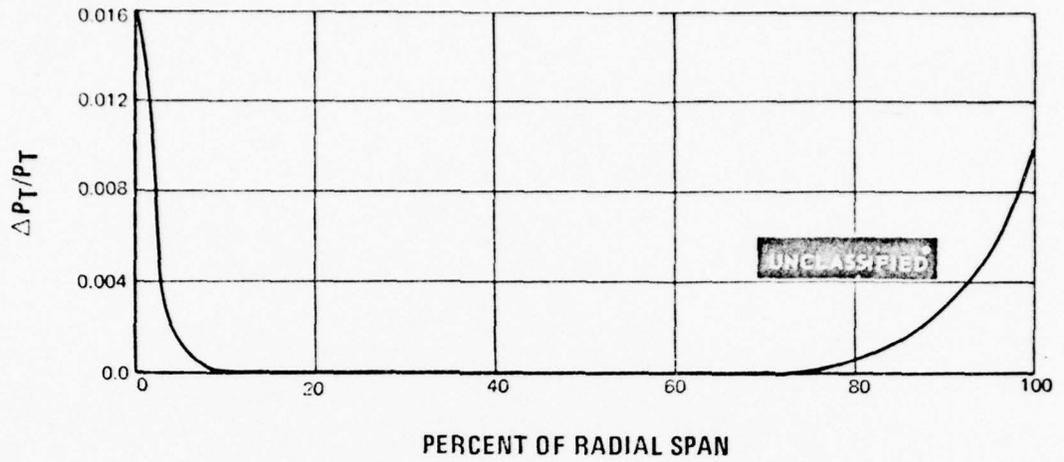


Figure 154 Inlet Guide Vane Spanwise Pressure Loss Distribution, Second Vane Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. = 0.860

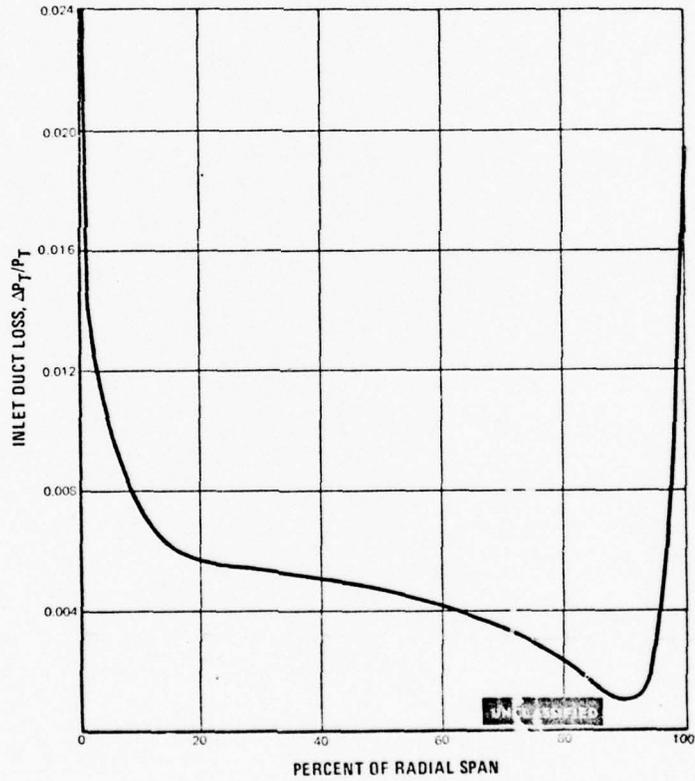


Figure 155 Inlet Guide Vane Spanwise Pressure Loss Distribution, Second Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. = 0.918

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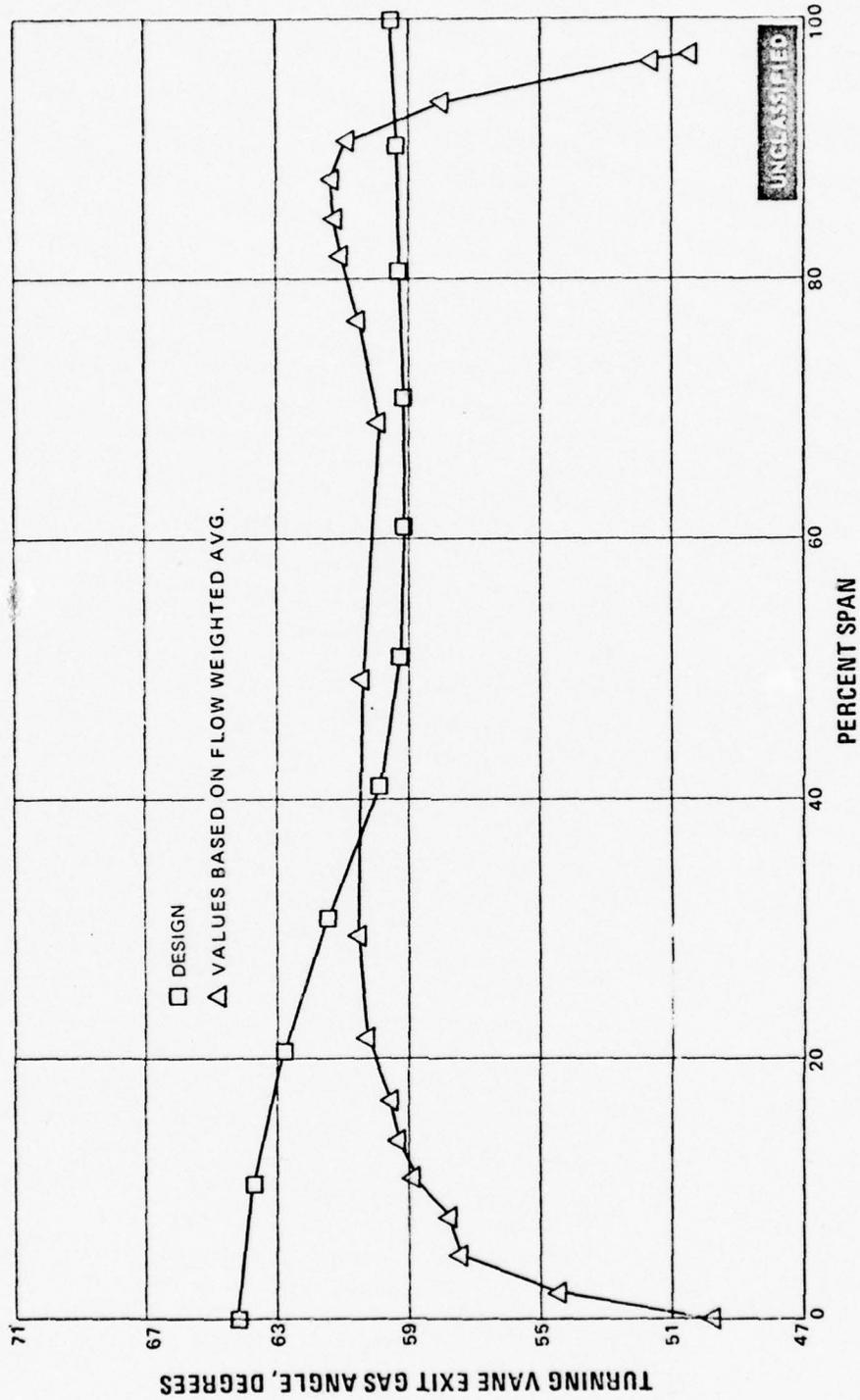


Figure 156 Inlet Guide Vane Spanwise Exit Angle Distribution, First Vane Medium Solidity Cascade--Midspan Exit Test Airfoil Mach No. = 0.835

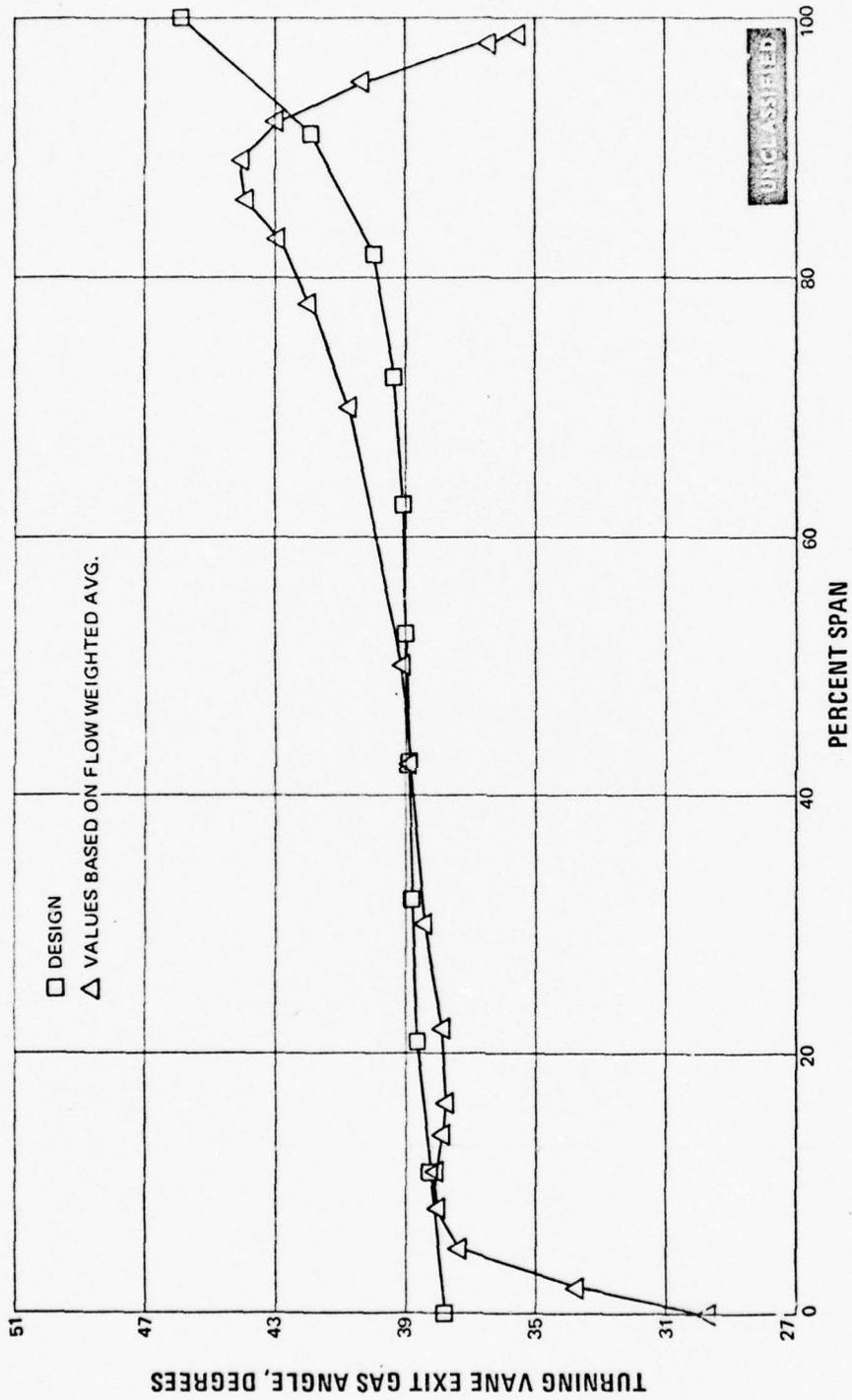


Figure 157 Inlet Guide Vane Spanwise Exit Angle Distribution, First Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. = 0.775

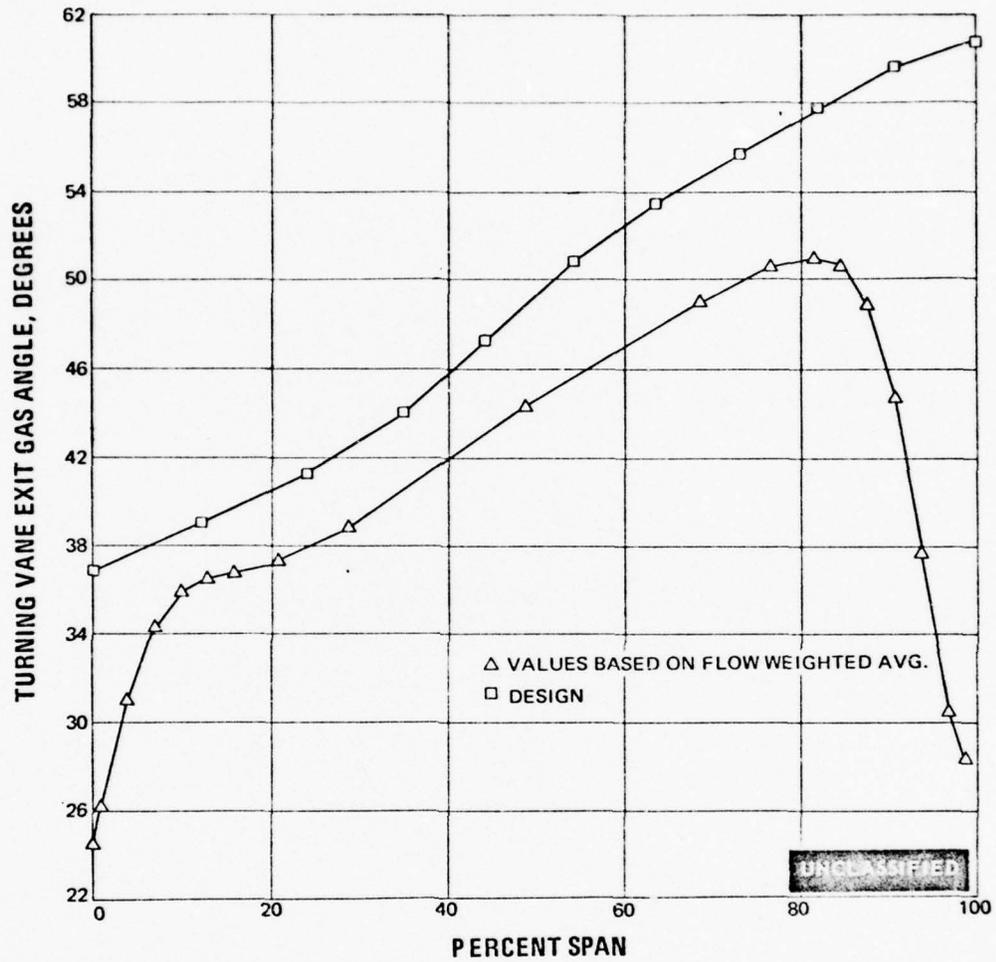


Figure 158 Inlet Guide Vane Spanwise Exit Angle Distribution, Second Vane Medium Solidity Cascade-Midspan Exit Test Airfoil Mach No. = 0.860

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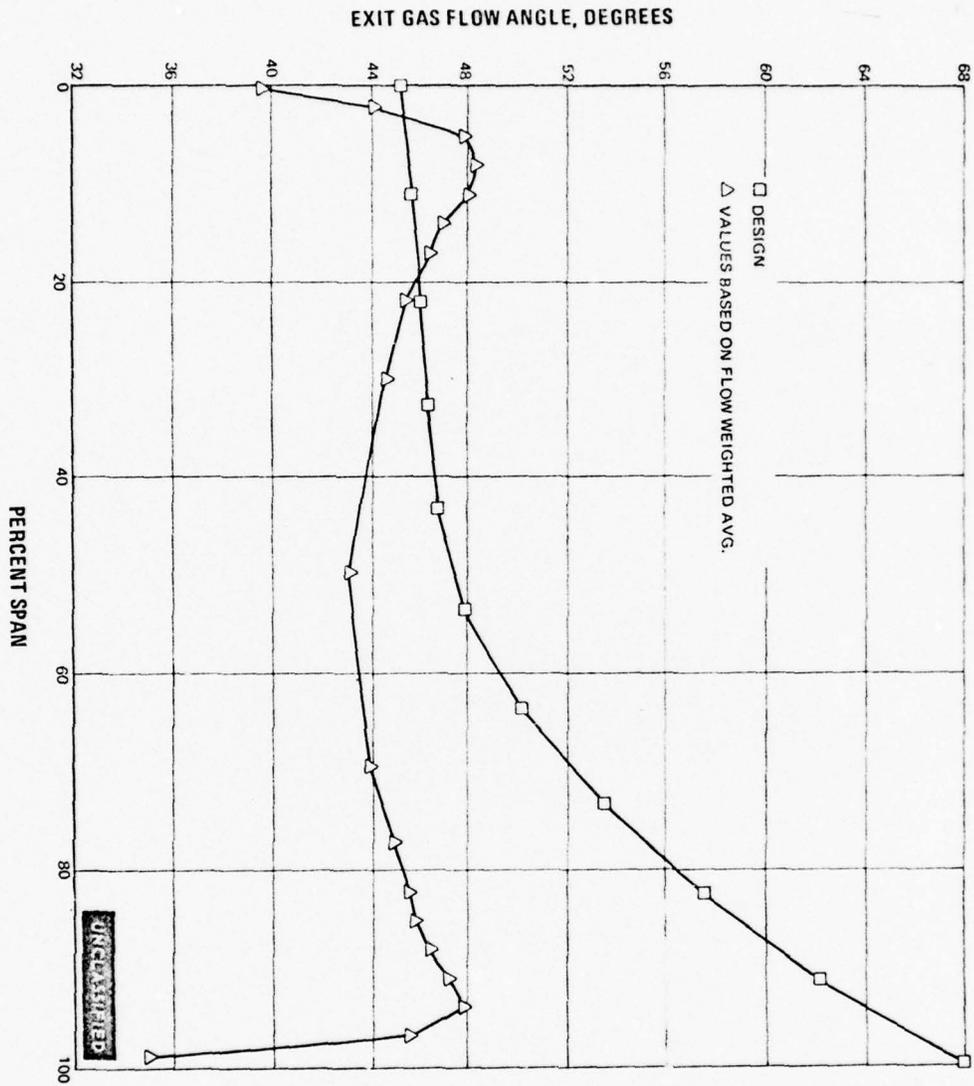


Figure 159 Inlet Guide Vane Spanwise Exit Angle Distribution, Second Blade Medium Solidity Cascade—Midspan Exit Test Airfoil Mach No. = 0.918

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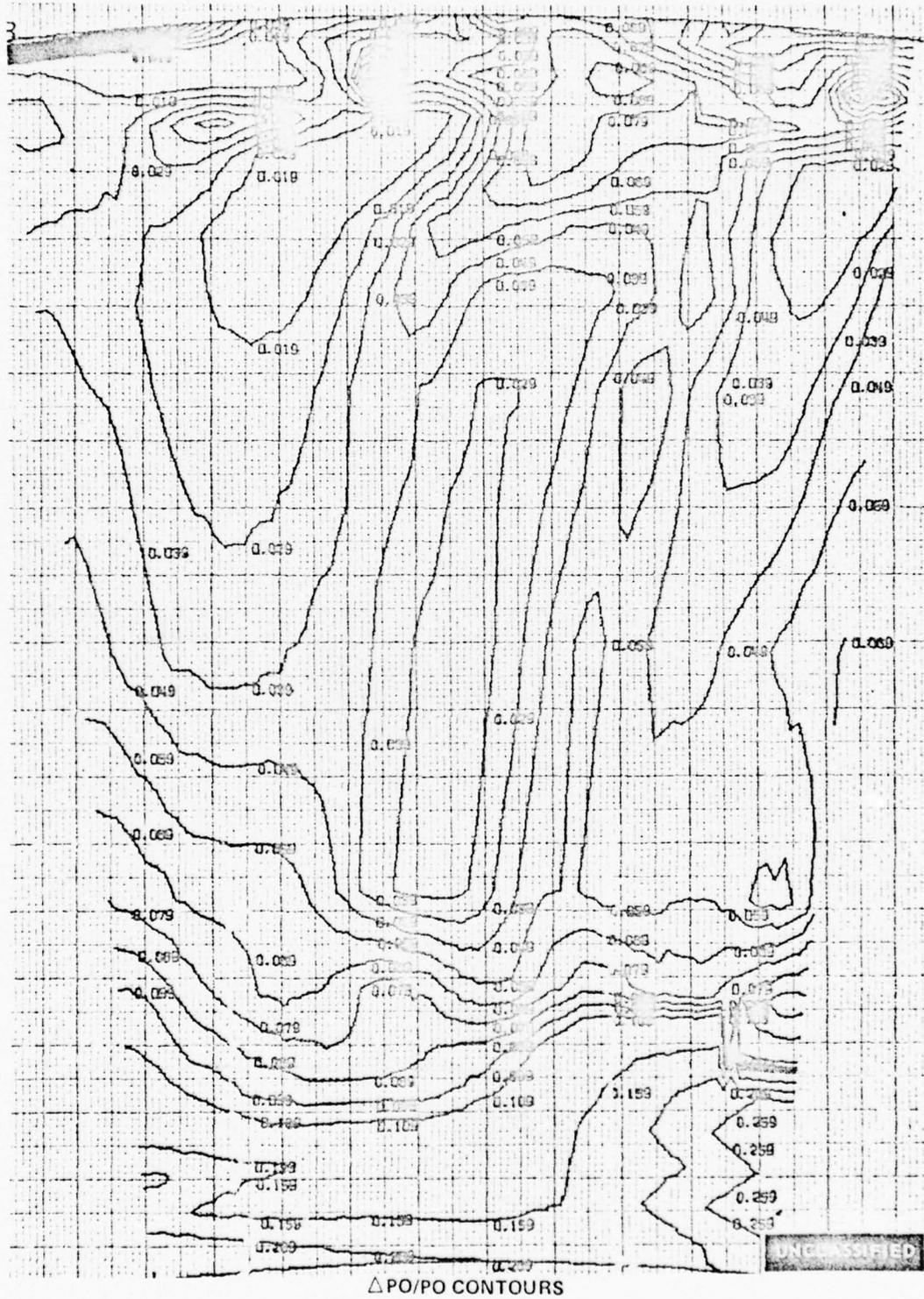
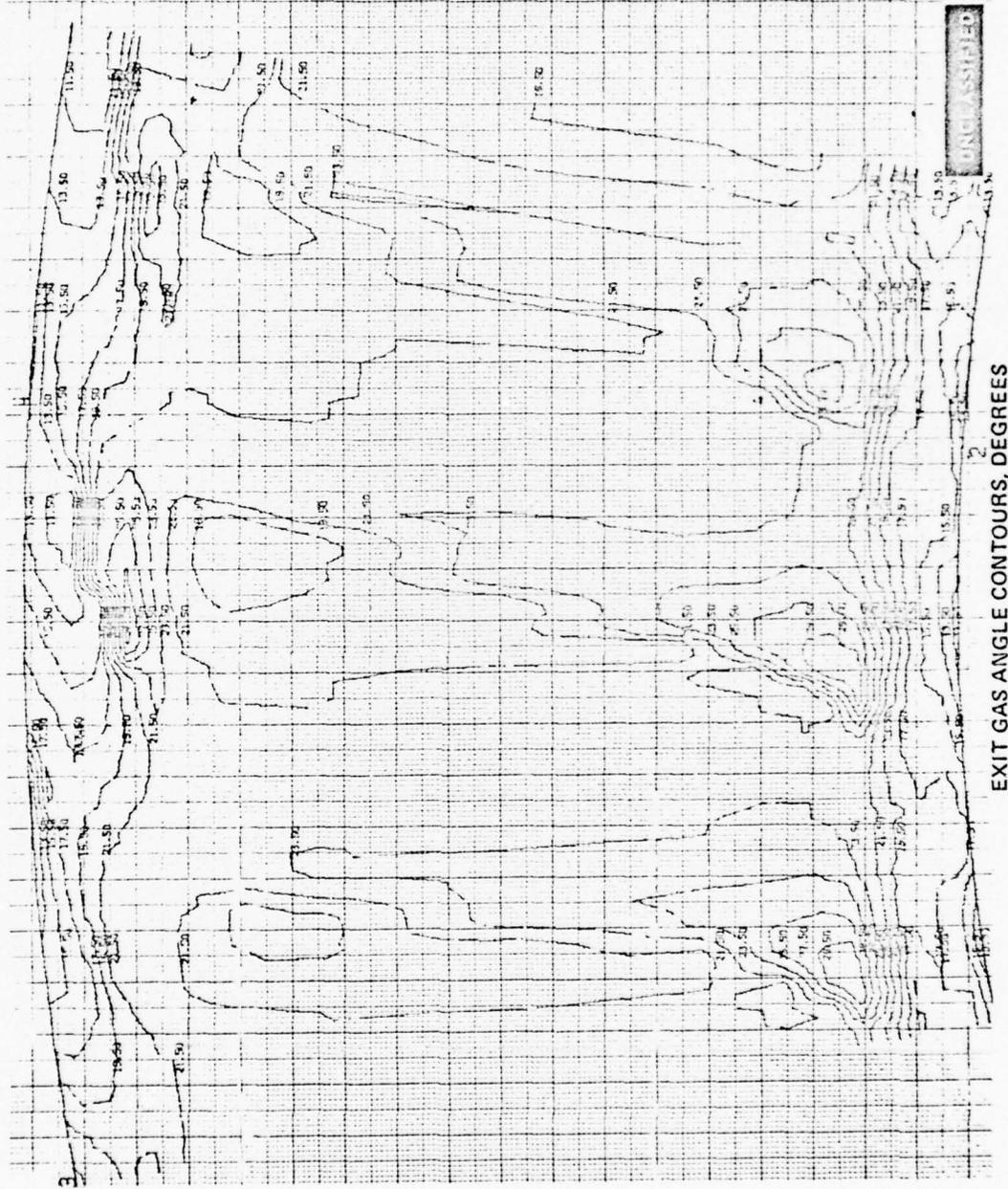


Figure 161 Pressure Loss Contours, First Blade, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. = 0.775

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EXIT GAS ANGLE CONTOURS, DEGREES

Figure 162 Exit Gas Angle Contours, First Vane, Medium Solidity, Three Flow Passages,  
Midspan Exit Mach No. = 0.835

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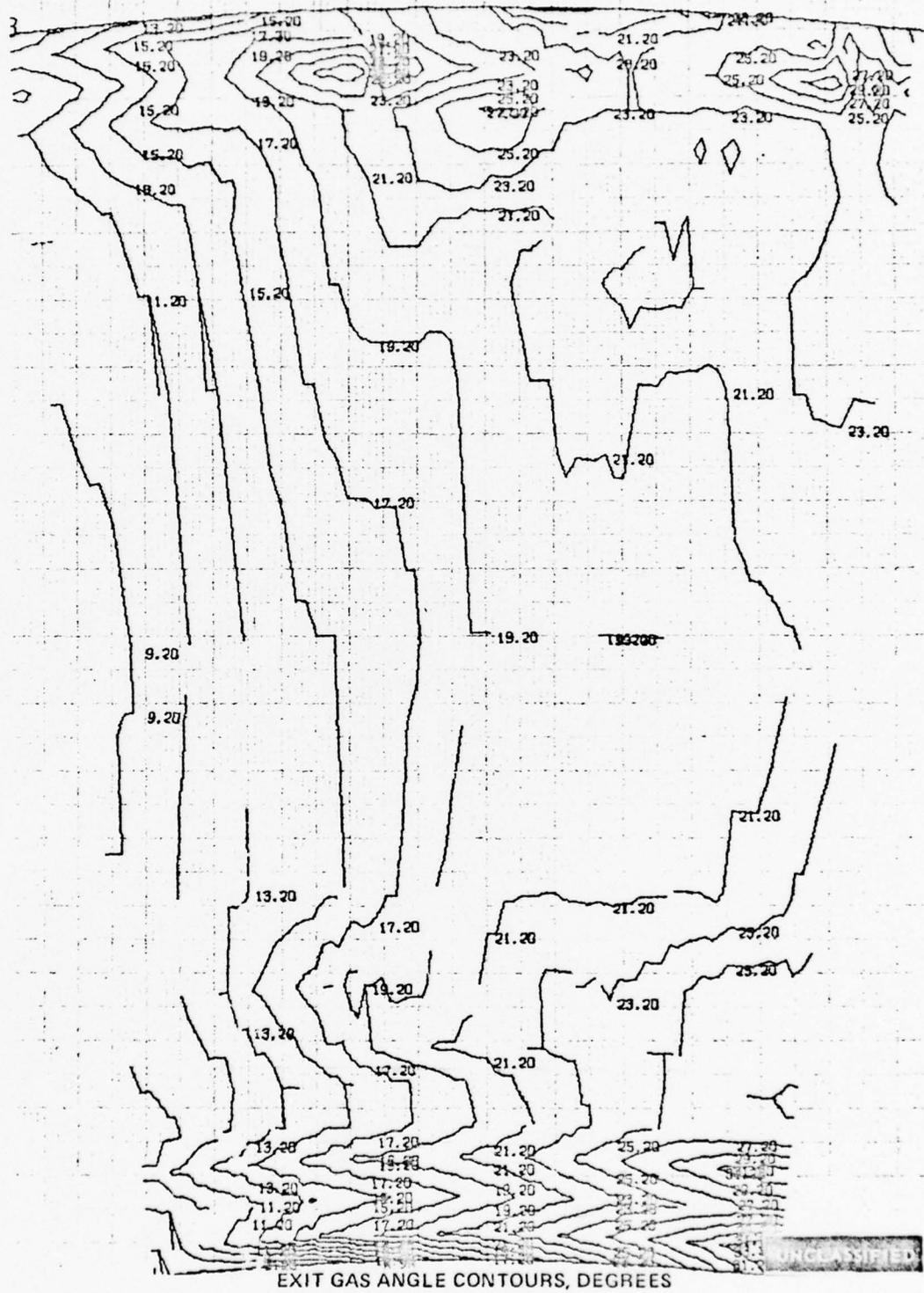


Figure 163 Exit Gas Angle Contours. First Blade, Medium Solidity, Three Flow Passages, Midspan Exit Mach No. = 0.775

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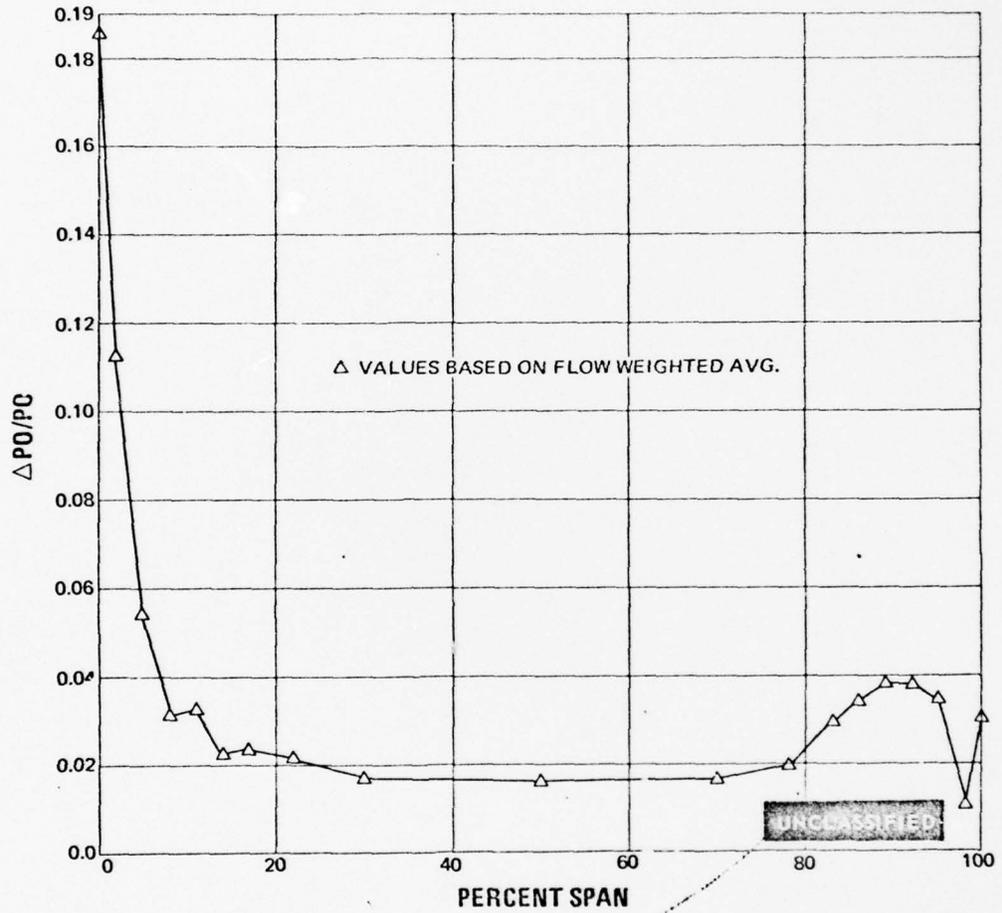


Figure 164 Spanwise Pressure Loss Distribution, First Vane, Medium Solidity, Midspan Exit Mach No. = 0.835

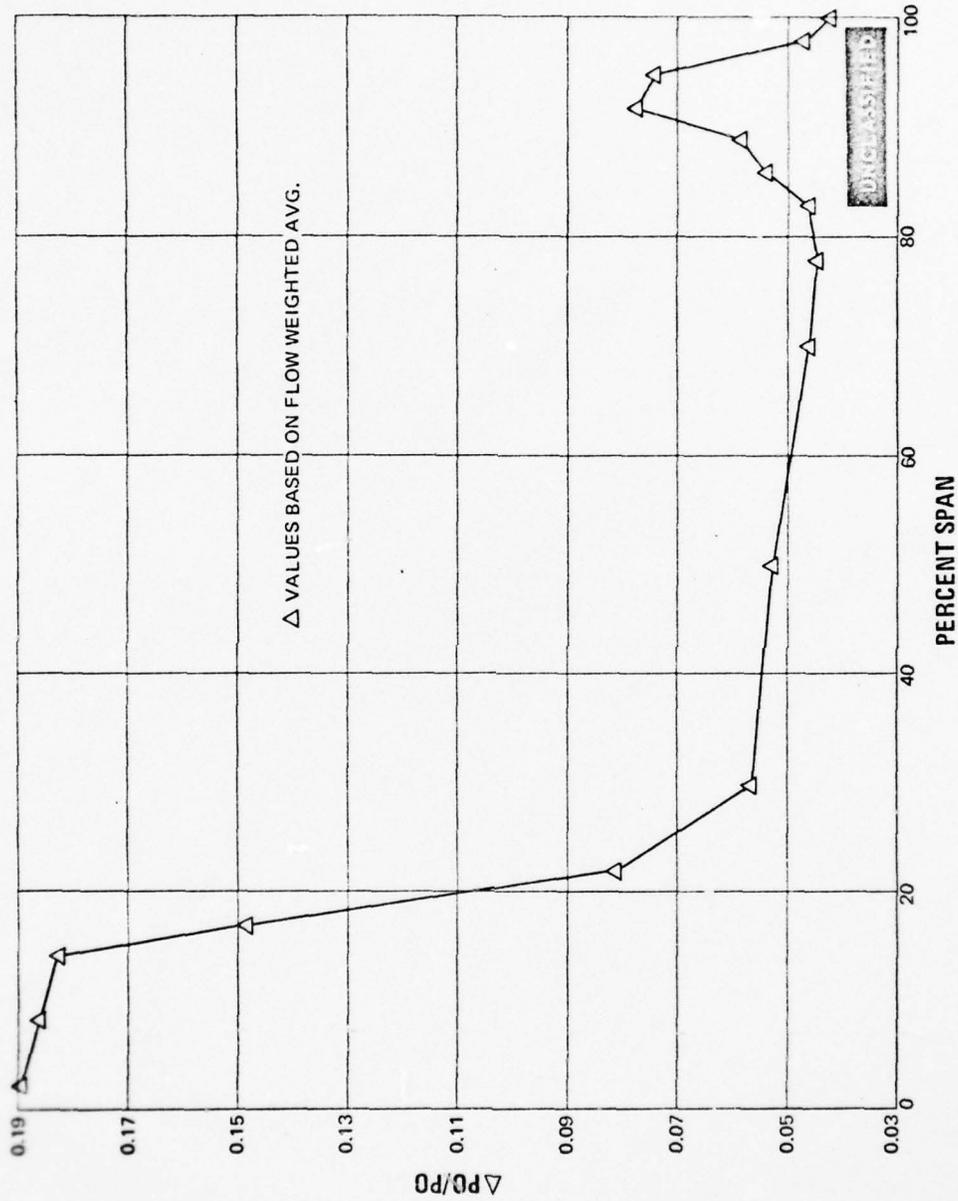


Figure 165 Spanwise Pressure Loss Distribution, First Blade, Medium Solidity, Midspan Exit  
Mach No. = 0.775

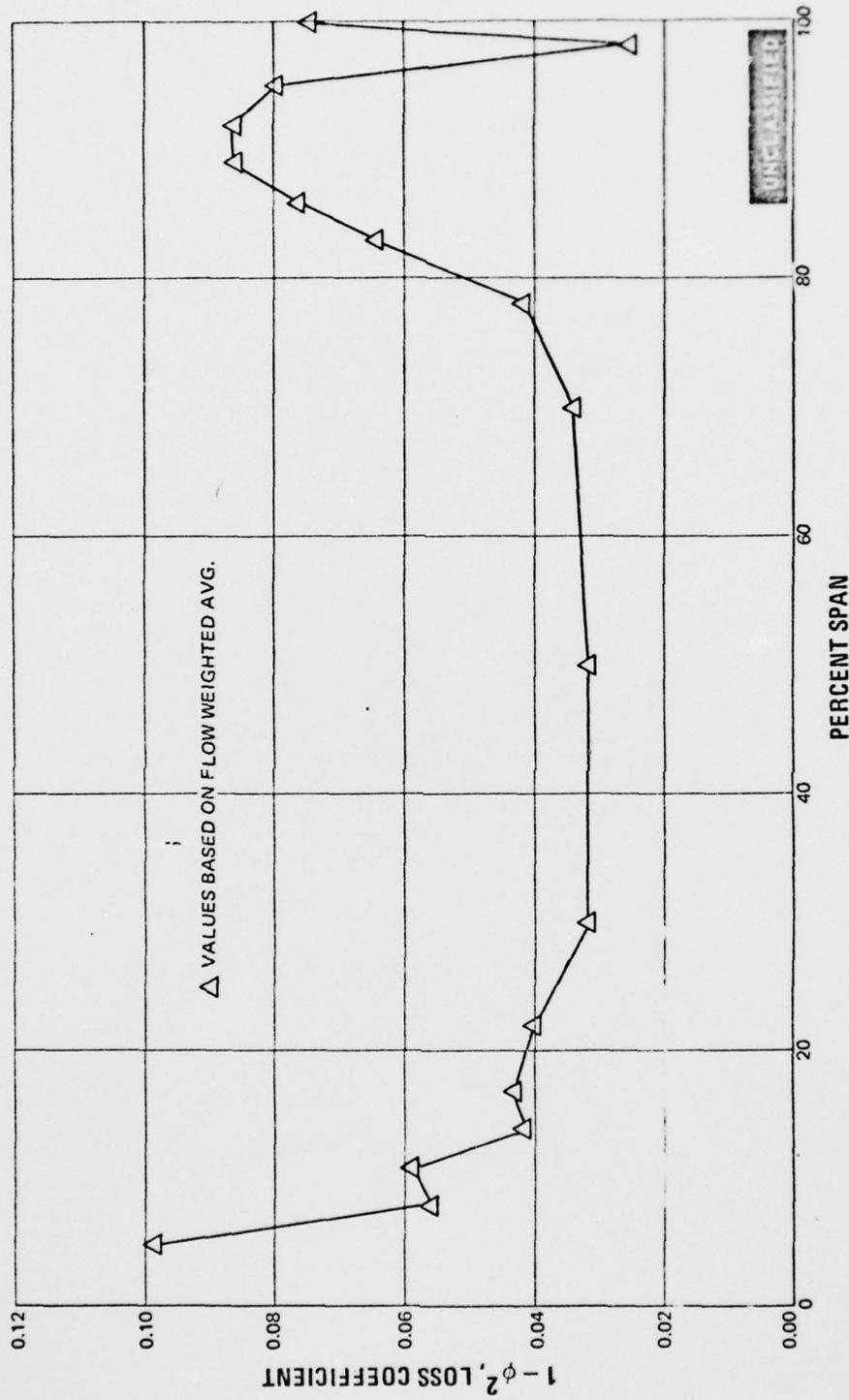


Figure 166 Spanwise Loss Coefficient Distribution, First Vane, Medium Solidity, Midspan  
Exit Mach No. = 0.835

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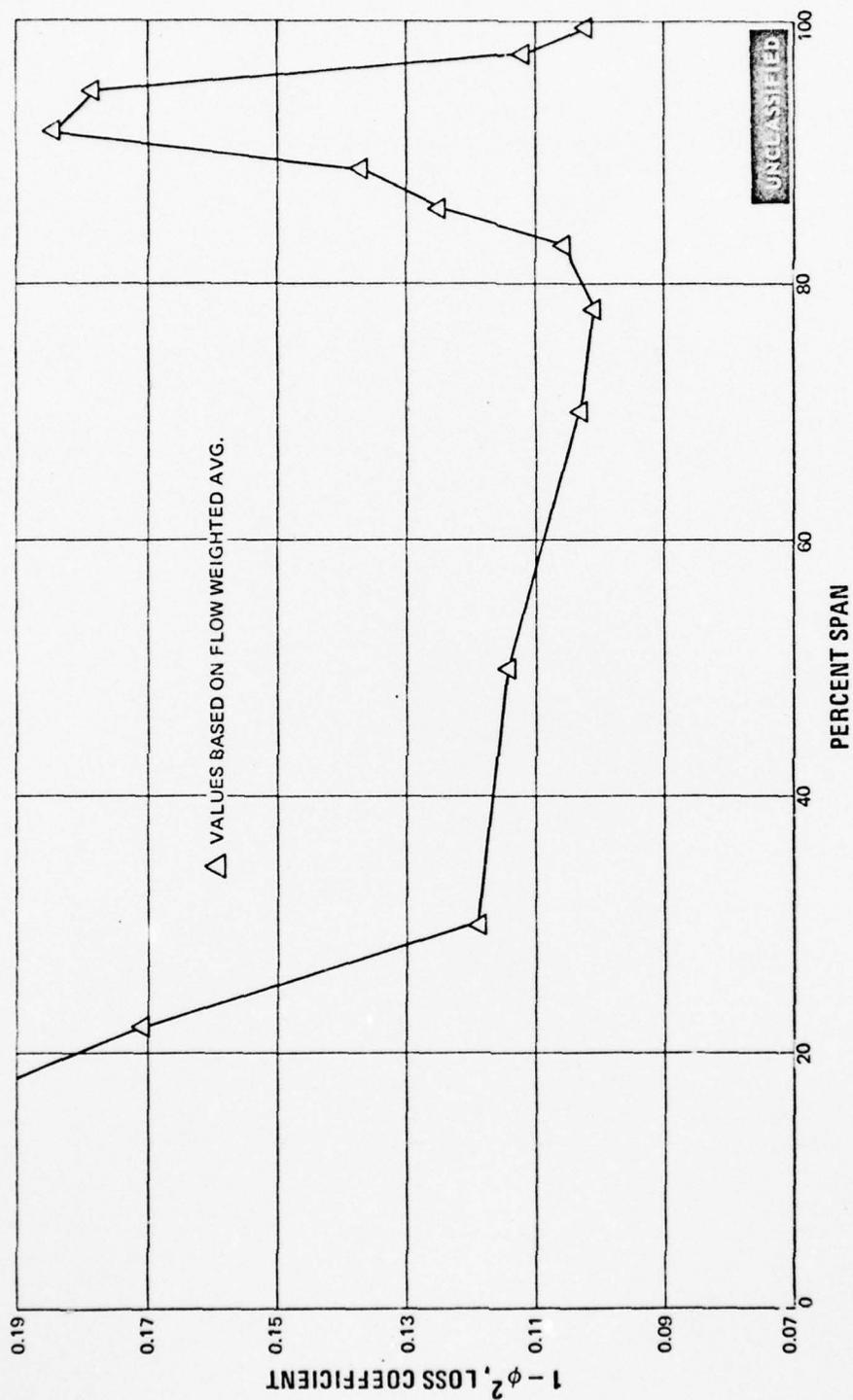


Figure 167 Spanwise Loss Coefficient Distribution, First Blade, Medium Solidity, Midspan  
Exit Mach No. = 0.775

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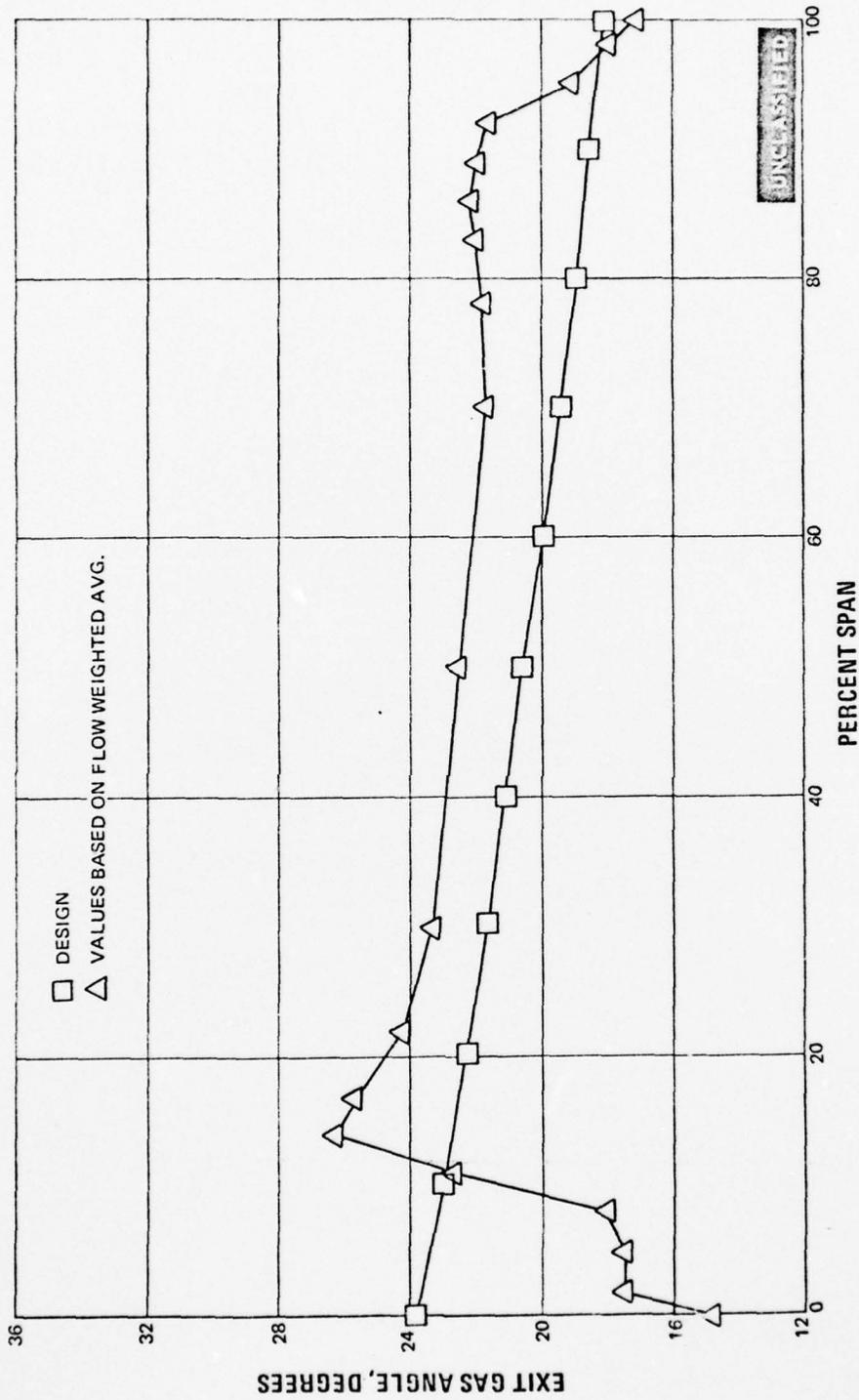


Figure 168 Spanwise Exit Gas Angle Distribution, First Vane, Medium Solidity, Midspan  
Exit Mach No. = 0.835

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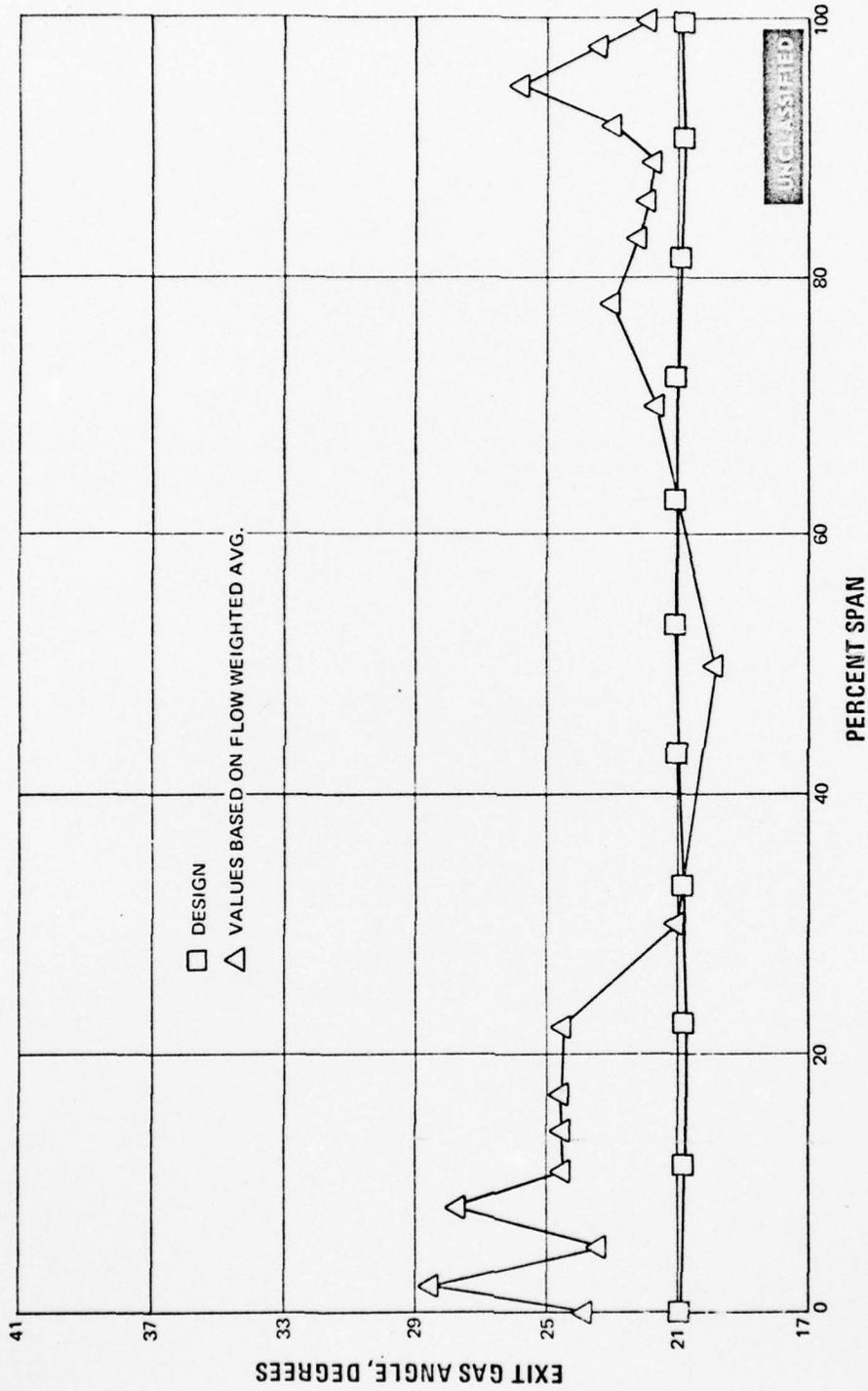


Figure 169 Spanwise Exit Gas Angle Distribution, First Blade, Medium Solidity, Midspan  
Exit Mach No. = 0.775

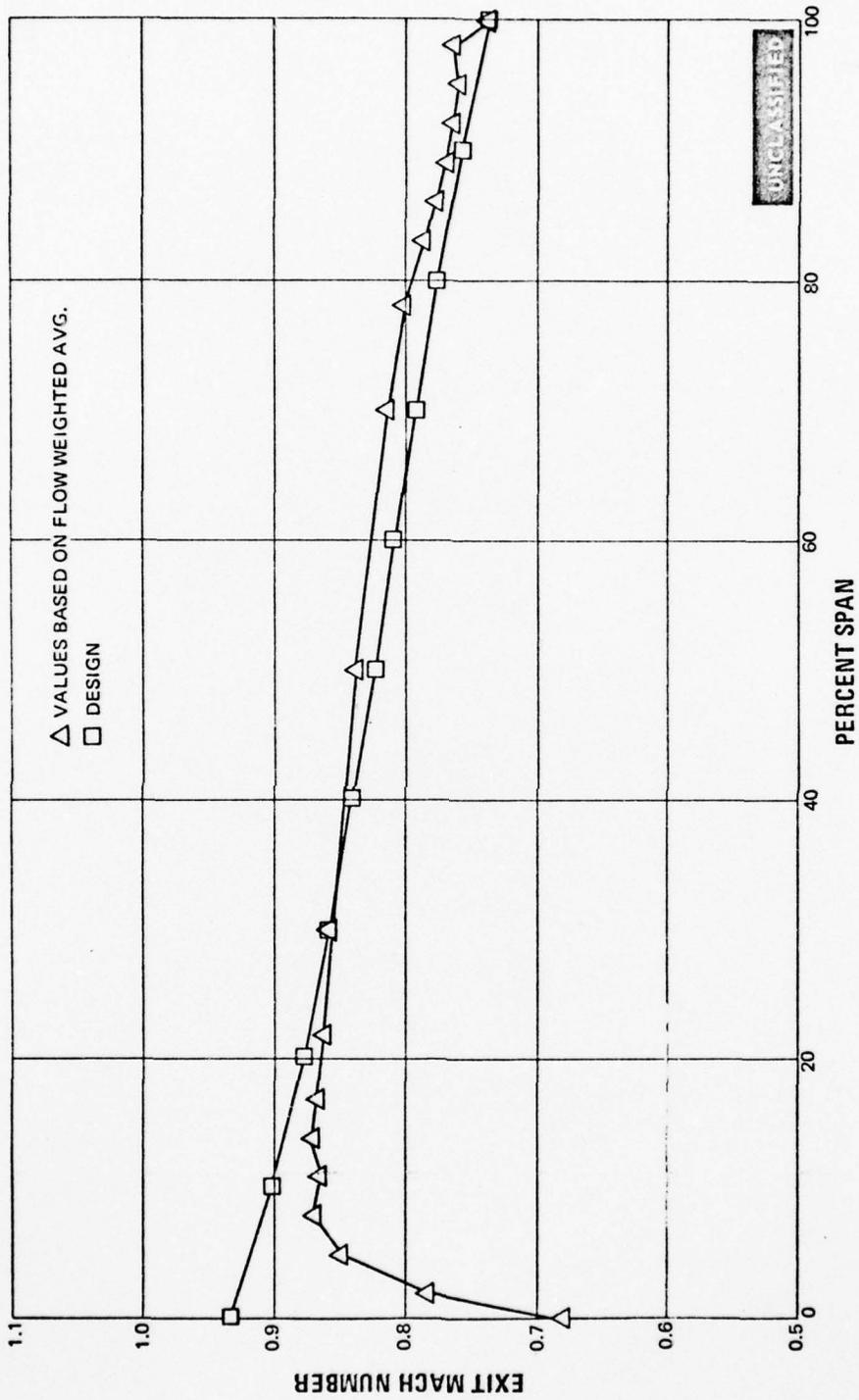


Figure 170 Spanwise Exit Mach Number Distribution, First Vane, Medium Solidity, Mid-span Exit Mach No. = 0.835

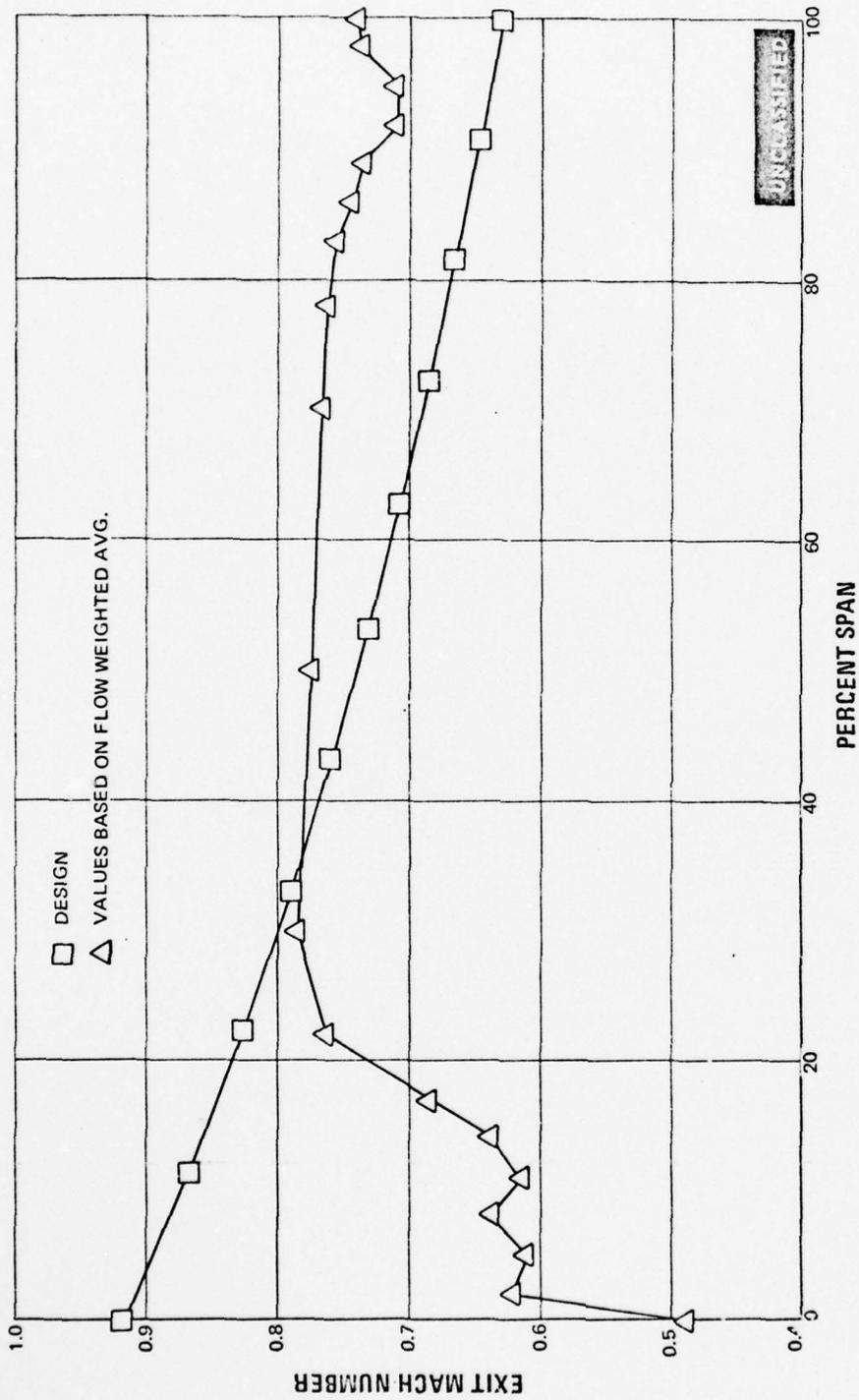


Figure 171 Spanwise Exit Mach Number Distribution, First Blade, Medium Solidity, Mid-span Exit Mach No. = 0.775

(U) The first vane airfoil cascade pressure loss contours (Figure 160) indicate low loss pockets over the midspan areas with the higher loss regions in the airfoil suction surface and end-wall corners. These losses originate at the end-wall and migrate from the pressure surface to the suction surface and accumulate in the corners. This is reflected in the plot of the average spanwise distribution of the total pressure loss (Figure 164) and loss coefficient (Figure 166) where the collection of end-wall loss is evident. The integrated overall loss coefficient for this airfoil is 0.050, and the midspan value is 0.0315 at a midspan exit Mach numbers of 0.835. The midspan loss coefficient predicted by boundary layer calculations is 0.025.

(U) The effect of Mach number and Reynolds Number on the midspan loss coefficient is shown in Table XXVI for the first vane. The loss levels change only within the experimental error with Mach number at constant design Reynolds Number. The loss level at constant Mach number has its lowest value (0.025) at 75 percent of design Reynolds Number, indicating that boundary layer transition point for this Reynolds Number is optimum (i.e., transition takes place just in time to prevent flow separation).

TABLE XXVI  
MEDIUM SOLIDITY  
FIRST VANE  
PROFILE LOSS COEFFICIENT VARIATIONS AT MEAN SECTION

$1 - \phi^2$

DESIGN:  $M = 0.854, R = 4.38 \times 10^5$

|         | 0.5R  | 0.75R | R      | 1.5R  |
|---------|-------|-------|--------|-------|
| M - 0.1 |       |       | 0.035  |       |
| M       | 0.047 | 0.025 | 0.0315 | 0.040 |
| M + 0.1 |       |       | 0.031  |       |

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(U) The airfoil exit gas angle contours (Figure 152) indicate close agreement with the design angles for the midspan portion of the first vane, with some overturning at the root and tip due to secondary flow. This is more clearly shown on the exit angle spanwise plot on which the design angles are also shown (Figure 158). The data gave no evidence of flow separation, and this was verified by visual observation of the oil and graphite flow patterns.

(U) Airfoil surface static pressure distribution at the root, mean and tip are shown in Figures 172 through 174. The experimental and predicted values are indicated on these plots. As noted from the circumferentially averaged Mach number distribution (Figure 170), the Mach number at the mean was very close to the design value, with a substantially lower Mach number at the root. Consequently, the experimental data dupli-

icated the predicted pressure distribution closely, and the root section indicates an unloaded airfoil. A similar problem, but to a lesser degree, exists at the tip section. As discussed in detail in the Reference 3 Report, the reason for this is the inability of the annular segment cascade to reproduce the desired static pressure gradient at the exit plane.

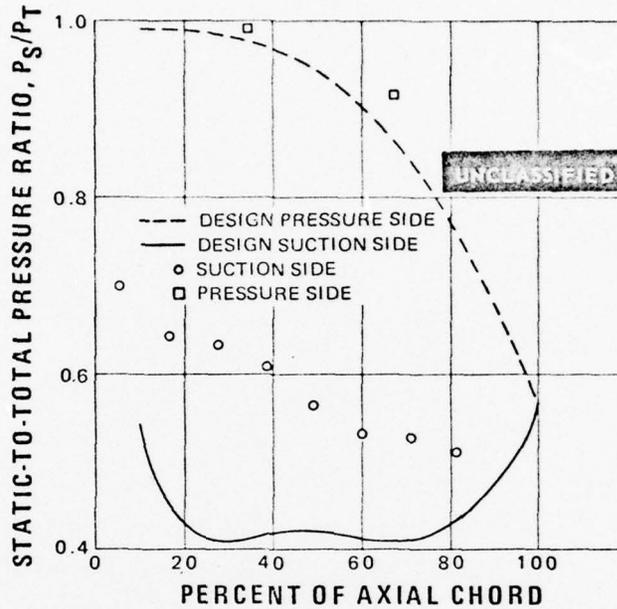


Figure 172 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity - Root Section

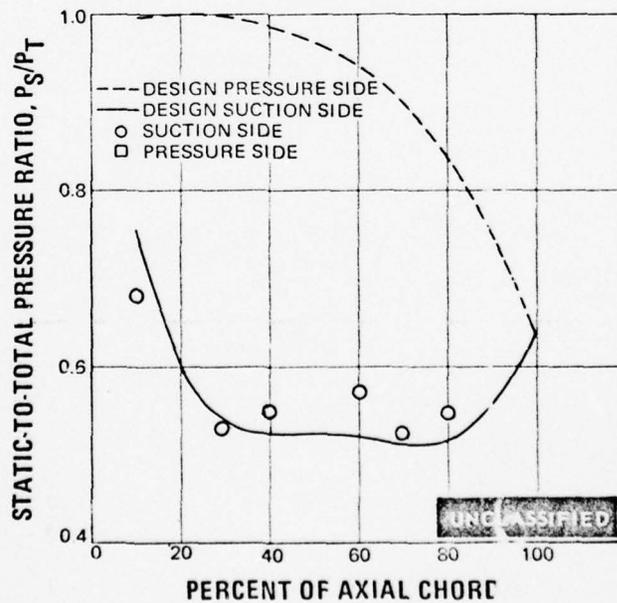


Figure 173 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity - Mean Section

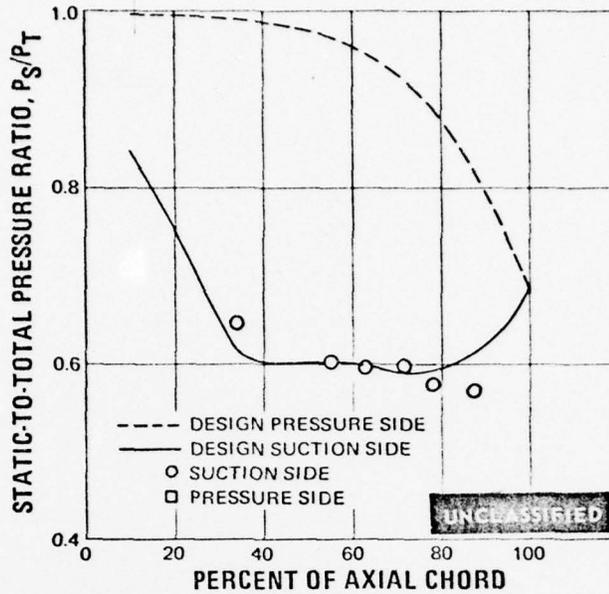


Figure 174 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Vane Medium Solidity - Tip Section

(U) The first blade airfoil cascade pressure loss contours (Figure 161) show a large loss pocket at the root section, indicating flow separation at the wall. The average spanwise pressure loss distribution (Figure 165) and loss coefficient (Figure 167) also show this to be the case. As noted in the Reference 2 Report, analyses were made to determine if potential problems of flow separation would exist on the inside end-wall extensions downstream of the test airfoil for each cascade design. Unfortunately, the end-wall extension for the first blade cascade was not sufficiently long to maintain a small enough pressure gradient to prevent separation. Some evidence of this was seen in the normal solidity first blade baseline evaluation, reported in the Reference 3 Report. The *traverse instrumentation* used on that cascade, however, was sufficiently close to the airfoil, so that the performance calibration was not adversely affected. The medium-solidity first blade cascade *traverse instrumentation* was located further downstream in the wall separated region, giving results which are not indicative of the airfoil performance.

(U) The airfoil surface static pressure distributions are presented for the first blade in Figures 175 through 177. The same comments apply to this data as to the surface pressure distributions for the first vane airfoil. Furthermore, the separated flow at the root section caused a major shift in the flow distribution, causing a large increase in Mach number at the tip section (Figure 171).

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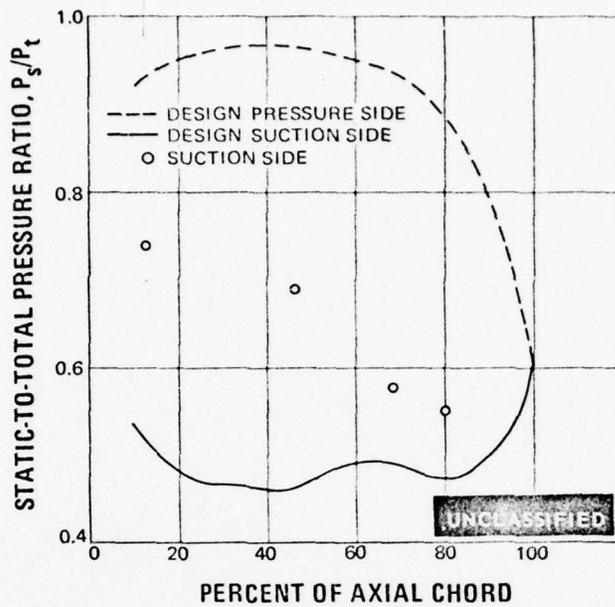


Figure 175 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity - Root Section

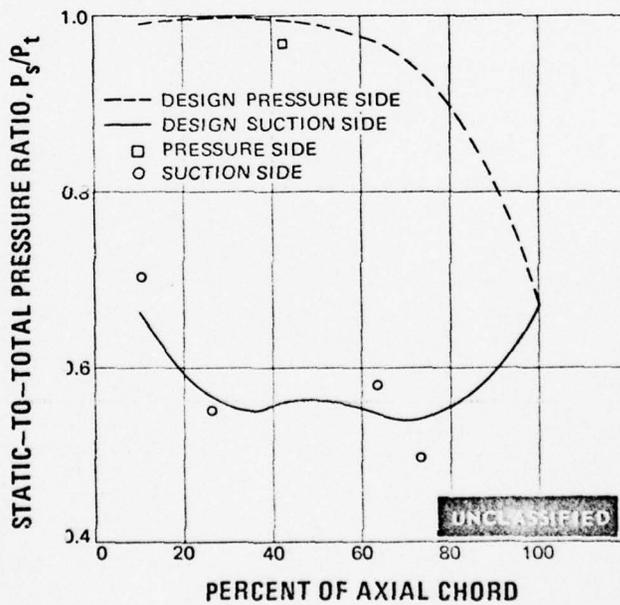


Figure 176 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity - Mean Section

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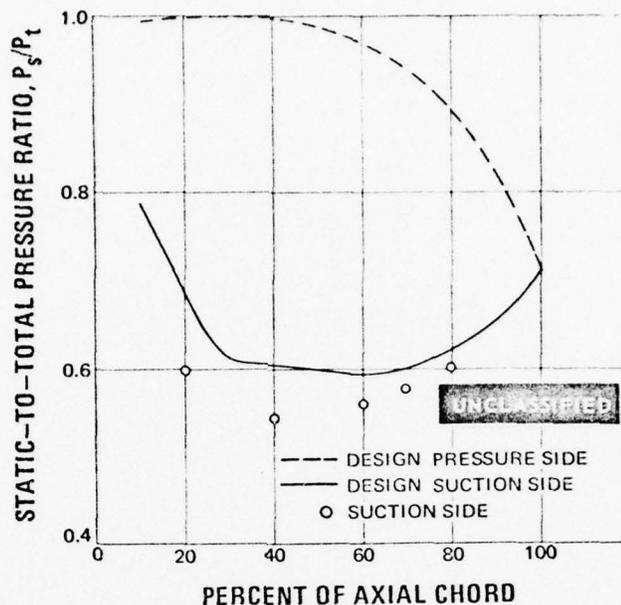


Figure 177 Static-to-Total Pressure Ratio versus Percent of Axial Chord, First Blade Medium Solidity - Tip Section

## 5. CONCLUSIONS

(U) Conclusions drawn as a result of the performance evaluation of the medium-solidity airfoils and comparisons with the normal solidity results will be reported in the next interim report, after completion of Task II.

## 6. TEST PROCEDURE

(U) The annular segment cascade tests of the medium solidity airfoils were performed in the Willgoos Laboratory at East Hartford on X-214A stand. These performance tests required various combinations of compressors and exhausters, as well as the test stand natural gas burner to attain the desired Mach numbers and Reynolds Numbers at the cascade exit plane. Test conditions were always chosen so as to prevent the condensation of atmospheric water vapor.

(U) For each of the four configurations, four tests were required for a complete performance evaluation at any test point. The first and second of these tests were the traversing of the test airfoil inlet and exit planes with the total pressure cobra probe. A third test to determine the pitch angle was conducted by traversing the test airfoil exit plane with the pitch angle probe. Finally, a flow visualization test was conducted. The procedure listed below was used for these tests:

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- The cascade test pack was installed on the stand and all of the fixed instrumentation was connected
- The traversing probe was installed either at the inlet or exit plane of the test airfoil
- The traversing probe was correctly located relative to the test airfoil
- The total pressure transducers for the traversing probe and data recording equipment were calibrated
- The laboratory compressors and exhausters which were required for the test were started and allowed to reach steady operating conditions (approximately 2 hrs.)
- Test stand burner was started and the required aerodynamic conditions were set at the cascade exit plane mean section
- Fixed instrumentation readings were recorded with traversing probe removed. This step was repeated after the midspan traverse, and at the conclusion of the test
- The cobra probe was traversed circumferentially at the nineteen required radial locations starting at the outer diameter. Data was simultaneously recorded on plotomat charts and punched onto computer cards
- The test to determine the pitch angle at the cascade exit plane was carried out using the preceding steps, except that the cobra probe was replaced by the pitch probe
- The flow visualization test was carried out with the exhaust plenum cover removed. For this final test the airfoils and end-walls of the cascade pack were painted with a layer of graphite and heavy oil. The air total temperature was set at about 100°F and the total pressure was set to give the required Mach number. Test stand safety rules prevented dumping of hotter air into the cell with the exhaust cover removed, thus preventing simulation of the design Reynolds Number. Air was allowed to flow through the cascade for one minute and the resulting patterns were observed. In order to determine if removal of this cover affected the cascade performance, a test was made where the cascade was traversed and the performance data obtained with the cover removed. There was no difference between this data, and data taken with the cover in place at the same flow conditions.

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SECTION VI  
PRELIMINARY DESIGN MANUAL PREPARATION (TASK IIc)

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PRATT AND WHITNEY AIRCRAFT GROUP EAST HARTFORD CONN F/G 21/5  
INVESTIGATION OF A HIGHLY LOADED TWO-STAGE FAN-DRIVE TURBINE. V--ETC(U)  
DEC 69 H WELNA, D E DAHLBERG, W H HEISER F33615-68-C-1208  
PWA-3827 AFAPL-TR-69-92-VOL-4 NL

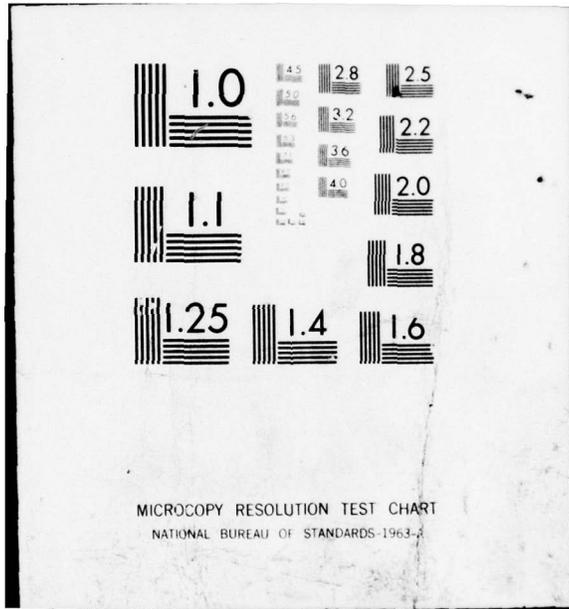
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## SECTION VI

### PRELIMINARY DESIGN MANUAL PREPARATION (TASK IIe)

#### 1. RFP OBJECTIVE

(U) Prepare the preliminary draft of the Turbine Design Procedure Manual.

#### 2. TASK OBJECTIVE

(U) The purpose of this task is to do preliminary work on the preparation of a Turbine Design Procedure Manual. This manual will contain the following information for each computer program used to design the Contract turbine: a flow diagram; a listing for all input and output items and their definitions; a list of definitions for each term used in the computer code; a write-up of the pertinent equations; a listing of the computer code in Fortran IV; a copy of the computer program decks in Fortran IV; any necessary test cases for deck check-out.

#### 3. STATUS

(U) All of the decks listed below have been converted to Fortran IV, checked out on an IBM 7094, and a tape containing these decks has been received by the Air Force. In addition, flow diagrams and test cases were also supplied. These decks included:

- Turbine Meanline Design Program
- Turbine Stage-Off Design Program
- Turbine Streamline Analysis Program
- Airfoil Pressure Distribution Program
- Airfoil Boundary Layer Program
- Turbine Airfoil Design and Section Properties Program
- Airfoil Curved Line Fairing Program
- Airfoil Straight Line Fairing Program

This completes the requirements of Task IIe.

(U) Engineering write-up of the above listed decks is in process, and rough drafts have been completed for most of these decks. The Turbine Meanline Design Program write-up has been received by the Air Force. Those remaining will be completed as part of the requirements for Task IIc, Design Procedure Manual Preparation.

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**APPENDIX**

**TABLE NOS. IV THROUGH XII**

**REDESIGNED SECOND VANE  
CASCADE TURNING VANE**

**TABLE NOS. XIII THROUGH XX  
RECONTOURED SECOND VANE**

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TABLE IV  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of Root Section = 7.5000  
Pitch = 1.5708

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.7443

| Percent X                          | Foil X                       | Foil Y Suction           | Foil Y (Circle) |
|------------------------------------|------------------------------|--------------------------|-----------------|
| 0.0                                | 0.0                          | 1.9060                   | 1.8810          |
| 0.01                               | 0.0325                       | 1.9060                   | 1.9060          |
| 0.02                               | 0.0650                       | 1.9058                   | 1.9058          |
| 0.03                               | 0.0975                       | 1.9052                   | 1.9052          |
| 0.04                               | 0.1300                       | 1.9044                   | 1.9044          |
| 0.05                               | 0.1625                       | 1.9032                   | 1.9032          |
| 0.10                               | 0.3250                       | 1.8926                   | 1.8926          |
| 0.15                               | 0.4875                       | 1.8737                   | 1.8737          |
| 0.20                               | 0.6500                       | 1.8462                   | 1.8462          |
| 0.25                               | 0.8125                       | 1.8098                   | 1.8098          |
| 0.30                               | 0.9750                       | 1.7642                   | 1.7642          |
| 0.35                               | 1.1375                       | 1.7091                   | 1.7091          |
| 0.40                               | 1.3000                       | 1.6443                   | 1.6443          |
| 0.45                               | 1.4625                       | 1.5694                   | 1.5694          |
| 0.50                               | 1.6250                       | 1.4842                   | 1.4842          |
| 0.55                               | 1.7875                       | 1.3885                   | 1.3885          |
| 0.60                               | 1.9500                       | 1.2822                   | 1.2822          |
| 0.65                               | 2.1125                       | 1.1649                   | 1.1649          |
| 0.70                               | 2.2750                       | 1.0367                   | 1.0367          |
| 0.75                               | 2.4375                       | 0.8975                   | 0.8975          |
| 0.80                               | 2.6000                       | 0.7470                   | 0.7470          |
| 0.85                               | 2.7625                       | 0.5854                   | 0.5854          |
| 0.90                               | 2.9250                       | 0.4127                   | 0.4127          |
| 0.95                               | 3.0875                       | 0.2289                   | 0.2289          |
| 0.98                               | 3.1850                       | 0.1101                   | 0.1101          |
| 0.99                               | 3.2175                       | 0.0718                   | 0.1718          |
| 1.00                               | 3.2500                       | 0.0339                   | 0.0250          |
| Foil L.E. Circle                   | X = 0.0250,                  | Y = 1.8810,              | R = 0.0250      |
| Foil T.E. Circle                   | X = 3.2250,                  | Y = 0.0250,              | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction     | X = 0.0250,                  | Y = 1.9060               |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0250,                  | Y = 1.8560               |                 |
| Foil T.E. Tangency Pt. Suction     | X = 3.2444,                  | Y = 0.0408               |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 3.2056,                  | Y = 0.0092               |                 |
| Foil Nose Point                    | X = 0.0                      | Y = 1.8810               |                 |
| Foil Tail Point                    | X = 3.2408,                  | Y = 0.0056               |                 |
| Foil Area (Less Core) = 0.1968     |                              |                          |                 |
| Gaging Gaging Angle                | LAMBDA = 1.0214,<br>= 40.561 | X = 2.5142,              | Y = 0.8279      |
| Center of Gravity Radial Reference | X = 1.7483,<br>X = 1.7483,   | Y = 1.2100<br>Y = 1.2100 |                 |
| Inlet Angle                        | = 90.000,                    | Delta Beta 1 = 0.001     |                 |
| Exit Angle                         | = 39.060,                    | Delta Beta 2 = 0.001     |                 |
| Uncovered Turning                  | = 8.198                      |                          |                 |
| Constant Section Thickness = .050  |                              |                          |                 |

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**TABLE V**  
**REDESIGNED SECOND VANE CASCADE TURNING VANE**

Radius of 1/8R Section = 7.8905  
Pitch = 1.6526

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.6746

| Percent X                          | Foil X                       | Foil Y Suction           | Foil Y (Circle) |
|------------------------------------|------------------------------|--------------------------|-----------------|
| 0.0                                | 0.0                          | 1.4951                   | 1.4701          |
| 0.01                               | 0.0325                       | 1.4950                   | 1.4950          |
| 0.02                               | 0.0650                       | 1.4949                   | 1.4949          |
| 0.03                               | 0.0975                       | 1.4945                   | 1.4945          |
| 0.04                               | 0.1300                       | 1.4939                   | 1.4939          |
| 0.05                               | 0.1625                       | 1.4930                   | 1.4930          |
| 0.10                               | 0.3250                       | 1.4849                   | 1.4849          |
| 0.15                               | 0.4875                       | 1.4702                   | 1.4702          |
| 0.20                               | 0.6500                       | 1.4485                   | 1.4485          |
| 0.25                               | 0.8125                       | 1.4192                   | 1.4192          |
| 0.30                               | 0.9750                       | 1.3817                   | 1.3817          |
| 0.35                               | 1.1375                       | 1.3353                   | 1.3353          |
| 0.40                               | 1.3000                       | 1.2797                   | 1.2797          |
| 0.45                               | 1.4625                       | 1.2143                   | 1.2143          |
| 0.50                               | 1.6250                       | 1.1384                   | 1.1384          |
| 0.55                               | 1.7875                       | 1.0518                   | 1.0518          |
| 0.60                               | 1.9500                       | 0.9540                   | 0.9540          |
| 0.65                               | 2.1125                       | 0.8449                   | 0.8449          |
| 0.70                               | 2.2750                       | 0.7243                   | 0.7243          |
| 0.75                               | 2.4375                       | 0.5922                   | 0.5922          |
| 0.80                               | 2.6000                       | 0.4489                   | 0.4489          |
| 0.85                               | 2.7625                       | 0.2944                   | 0.2944          |
| 0.90                               | 2.9250                       | 0.1291                   | 0.1291          |
| 0.95                               | 3.0875                       | -0.0468                  | -0.0468         |
| 0.98                               | 3.1850                       | -0.1602                  | -0.1602         |
| 0.99                               | 3.2175                       | -0.1978                  | -0.1978         |
| 1.00                               | 3.2500                       | -0.2331                  | -0.2422         |
| Foil L.E. Circle                   | X = 0.0250,                  | Y = 1.4701,              | R = 0.0250      |
| Foil T.E. Circle                   | X = 3.2250,                  | Y = -0.2422,             | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction     | X = 0.0250,                  | Y = 1.4951               |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0250,                  | Y = 1.4451               |                 |
| Foil T.E. Tangency Pt. Suction     | X = 3.2441,                  | Y = -0.2260              |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 3.2059,                  | Y = -0.2584              |                 |
| Foil Nose Point                    | X = 0.0                      | Y = 1.4701               |                 |
| Foil Tail Point                    | X = 3.2412,                  | Y = -0.2613              |                 |
| Foil Area (Less Core) = 0.1915     |                              |                          |                 |
| Gaging Gaging Angle                | LAMBDA = 1.1087,<br>= 42.135 | X = 2.4816,              | Y = 0.5545      |
| Center of Gravity Radial Reference | X = 1.7469,<br>X = 1.7483,   | Y = 0.8682<br>Y = 1.2100 |                 |
| Inlet Angle                        | = 90.000,                    | Delta Beta 1 = 0.001     |                 |
| Exit Angle                         | = 40.355,                    | Delta Beta 2 = 0.001     |                 |
| Uncovered Turning                  | = 8.737                      |                          |                 |
| Constant Section Thickness = .050  |                              |                          |                 |

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**TABLE VI**  
**REDESIGNED SECOND VANE CASCADE TURNING VANE**

|   |   |                       |                    |
|---|---|-----------------------|--------------------|
| Radius of 1/4R Section = 8.2810<br>Pitch = 1.7344 | Axial Chord = 3.2500<br>No. of Foils = 4. | Actual Chord = 3.6127 |                    |
| Percent<br>X                                      | Foil X                                    | Foil Y<br>Suction     | Foil Y<br>(Circle) |
| 0.0   | 0.0                                       | 1.1160                | 1.0910             |
| 0.01  | 0.0325                                    | 1.1160                | 1.1160             |
| 0.02  | 0.0650                                    | 1.1159                | 1.1159             |
| 0.03  | 0.0975                                    | 1.1155                | 1.1155             |
| 0.04  | 0.1300                                    | 1.1150                | 1.1150             |
| 0.05  | 0.1625                                    | 1.1143                | 1.1143             |
| 0.10  | 0.3250                                    | 1.1077                | 1.1077             |
| 0.15  | 0.4875                                    | 1.0955                | 1.0955             |
| 0.20  | 0.6500                                    | 1.0772                | 1.0772             |
| 0.25  | 0.8125                                    | 1.0521                | 1.0521             |
| 0.30  | 0.9750                                    | 1.0196                | 1.0196             |
| 0.35  | 1.1375                                    | 0.9791                | 0.9791             |
| 0.40  | 1.3000                                    | 0.9298                | 0.9298             |
| 0.45  | 1.4625                                    | 0.8712                | 0.8712             |
| 0.50  | 1.6250                                    | 0.8026                | 0.8026             |
| 0.55  | 1.7875                                    | 0.7236                | 0.7236             |
| 0.60  | 1.9500                                    | 0.6337                | 0.6337             |
| 0.65  | 2.1125                                    | 0.5328                | 0.5328             |
| 0.70  | 2.2750                                    | 0.4207                | 0.4207             |
| 0.75  | 2.4375                                    | 0.2974                | 0.2974             |
| 0.80  | 2.6000                                    | 0.1633                | 0.1633             |
| 0.85  | 2.7625                                    | 0.0186                | 0.0186             |
| 0.90  | 2.9250                                    | -0.1362               | -0.1362            |
| 0.95  | 3.0875                                    | -0.3010               | -0.3010            |
| 0.98  | 3.1850                                    | -0.4063               | -0.4063            |
| 0.99  | 3.2175                                    | -0.4412               | -0.4412            |
| 1.00  | 3.2500                                    | -0.4753               | -0.4850            |
| Foil L.E. Circle                                  | X = 0.0250,                               | Y = 1.0910,           | R = 0.0250         |
| Foil T.E. Circle                                  | X = 3.2250,                               | Y = -0.4850,          | R = 0.0250         |
| Foil L.E. Tangency Pt. Suction                    | X = 0.0250,                               | Y = 1.1160            |                    |
| Foil L.E. Tangency Pt. Pressure                   | X = 0.0250,                               | Y = 1.0660            |                    |
| Foil T.E. Tangency Pt. Suction                    | X = 3.2435,                               | Y = -0.4682           |                    |
| Foil T.E. Tangency Pt. Pressure                   | X = 3.2065,                               | Y = -0.5018           |                    |
| Foil Nose Point                                   | X = 0.0                                   | Y = 1.0910            |                    |
| Foil Tail Point                                   | X = 3.2418,                               | Y = -0.5035           |                    |
| Foil Area (Less Core) = 0.855                     |   |                       |                    |
| Gaging  | LAMBDA = 1.2102,                          | X = 2.4540,           | Y = 0.2843         |
| Gaging Angle                                      | = 44.250                                  |                       |                    |
| Center of Gravity                                 | X = 1.7356,                               | Y = 0.5496            |                    |
| Radial Reference                                  | X = 1.7483,                               | Y = 1.2100            |                    |
| Inlet Angle                                       | = 90.000,                                 | Delta Beta 1 = 0.001  |                    |
| Exit Angle  | = 42.300,                                 | Delta Beta 2 = 0.001  |                    |
| Uncovered Turning                                 | = 9.080                                   |                       |                    |
| Constant Section Thickness = .050                 |   |                       |                    |

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**TABLE VII**  
**REDESIGNED SECOND VANE CASCADE TURNING VANE**

|                                   |                      |                       |                    |
|-----------------------------------|----------------------|-----------------------|--------------------|
| Radius of 3/8R Section = 8.6715   | Axial Chord = 3.2500 | Actual Chord = 3.5567 |                    |
| Pitch = 1.8162                    | No. of Foils = 4     |                       |                    |
| Percent<br>X                      | Foil X               | Foil Y<br>Suction     | Foil Y<br>(Circle) |
| 0.0                               | 0.0                  | 0.7617                | 0.7367             |
| 0.01                              | 0.0325               | 0.7617                | 0.7617             |
| 0.02                              | 0.0650               | 0.7615                | 0.7615             |
| 0.03                              | 0.0975               | 0.7613                | 0.7613             |
| 0.04                              | 0.1300               | 0.7609                | 0.7609             |
| 0.05                              | 0.1625               | 0.7603                | 0.7603             |
| 0.10                              | 0.3250               | 0.7541                | 0.7541             |
| 0.15                              | 0.4875               | 0.7427                | 0.7427             |
| 0.20                              | 0.6500               | 0.7261                | 0.7261             |
| 0.25                              | 0.8125               | 0.7029                | 0.7029             |
| 0.30                              | 0.9750               | 0.6731                | 0.6731             |
| 0.35                              | 1.1375               | 0.6357                | 0.6357             |
| 0.40                              | 1.3000               | 0.5905                | 0.5905             |
| 0.45                              | 1.4625               | 0.5367                | 0.5367             |
| 0.50                              | 1.6250               | 0.4739                | 0.4739             |
| 0.55                              | 1.7875               | 0.4015                | 0.4015             |
| 0.60                              | 1.9500               | 0.3192                | 0.3192             |
| 0.65                              | 2.1125               | 0.2268                | 0.2268             |
| 0.70                              | 2.2750               | 0.1241                | 0.1241             |
| 0.75                              | 2.4375               | 0.0112                | 0.0112             |
| 0.80                              | 2.6000               | -0.1115               | -0.1115            |
| 0.85                              | 2.7625               | -0.2440               | -0.2440            |
| 0.90                              | 2.9250               | -0.3859               | -0.3859            |
| 0.95                              | 3.0875               | -0.5368               | -0.5368            |
| 0.98                              | 3.1850               | -0.6299               | -0.6299            |
| 0.99                              | 3.2175               | -0.6641               | -0.6641            |
| 1.00                              | 3.2500               | -0.6966               | -0.7069            |
| Foil L.E. Circle                  | X = 0.0250,          | Y = 0.7367,           | R = 0.0250         |
| Foil T.E. Circle                  | X = 3.2250,          | Y = -0.7069,          | R = 0.0250         |
| Foil L.E. Tangency Pt. Suction    | X = 0.0250,          | Y = 0.7617            |                    |
| Foil L.E. Tangency Pt. Pressure   | X = 0.0250,          | Y = 0.7117            |                    |
| Foil T.E. Tangency Pt. Suction    | X = 3.2427,          | Y = -0.6893           |                    |
| Foil T.E. Tangency Pt. Pressure   | X = 3.2073,          | Y = -0.7245           |                    |
| Foil Nose Point                   | X = 0.0,             | Y = 0.7367            |                    |
| Foil Tail Point                   | X = 3.2426,          | Y = -0.7246           |                    |
| Foil Area (Less Core) = 0.1790    |                      |                       |                    |
| Gaging                            | LAMBDA = 1.3262,     | X = 2.4321,           | Y = 0.0152         |
| Gaging Angle                      | = 46.906             |                       |                    |
| Center of Gravity                 | X = 1.7155,          | Y = 0.2492            |                    |
| Radial Reference                  | X = 1.7483,          | Y = 1.2100            |                    |
| Inlet Angle                       | = 90.000,            | Delta Beta 1 = 0.001  |                    |
| Exit Angle                        | = 44.825,            | Delta Beta 2 = 0.001  |                    |
| Uncovered Turning                 | = 9.303              |                       |                    |
| Constant Section Thickness = .050 |                      |                       |                    |

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TABLE VIII  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of Mean Section = 9.0625  
Pitch = 1.8980

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.4991

| Percent X                         | Foil X           | Foil Y Suction       | Foil Y (Circle) |
|-----------------------------------|------------------|----------------------|-----------------|
| 0.0                               | 0.0              | 0.3960               | 0.3710          |
| 0.01                              | 0.0325           | 0.3960               | 0.3960          |
| 0.02                              | 0.0650           | 0.3959               | 0.3959          |
| 0.03                              | 0.0975           | 0.3956               | 0.3956          |
| 0.04                              | 0.1300           | 0.3952               | 0.3952          |
| 0.05                              | 0.1625           | 0.3946               | 0.3946          |
| 0.10                              | 0.3250           | 0.3889               | 0.3889          |
| 0.15                              | 0.4875           | 0.3787               | 0.3787          |
| 0.20                              | 0.6500           | 0.3633               | 0.3633          |
| 0.25                              | 0.8125           | 0.3424               | 0.3424          |
| 0.30                              | 0.9750           | 0.3154               | 0.3154          |
| 0.35                              | 1.1375           | 0.2819               | 0.2819          |
| 0.40                              | 1.3000           | 0.2413               | 0.2413          |
| 0.45                              | 1.4625           | 0.1931               | 0.1931          |
| 0.50                              | 1.6250           | 0.1369               | 0.1369          |
| 0.55                              | 1.7875           | 0.0723               | 0.0723          |
| 0.60                              | 1.9500           | -0.0011              | -0.0011         |
| 0.65                              | 2.1125           | -0.0835              | -0.0835         |
| 0.70                              | 2.2750           | -0.1751              | -0.1751         |
| 0.75                              | 2.4375           | -0.2759              | -0.2759         |
| 0.80                              | 2.6000           | -0.3859              | -0.3859         |
| 0.85                              | 2.7625           | -0.5049              | -0.5049         |
| 0.90                              | 2.9250           | -0.6327              | -0.6327         |
| 0.95                              | 3.0875           | -0.7691              | -0.7691         |
| 0.98                              | 3.1850           | -0.8552              | -0.8552         |
| 0.99                              | 3.2175           | -0.8779              | -0.8779         |
| 1.00                              | 3.2500           | -0.9140              | -0.9250         |
| Foil L.E. Circle                  | X = 0.0250,      | Y = 0.3710,          | R = 0.0250      |
| Foil T.E. Circle                  | X = 3.2250,      | Y = -0.9250,         | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction    | X = 0.0250,      | Y = 0.3960           |                 |
| Foil L.E. Tangency Pt. Pressure   | X = 0.0250,      | Y = 0.3460           |                 |
| Foil T.E. Tangency Pt. Suction    | X = 3.2419,      | Y = -0.9066          |                 |
| Foil T.E. Tangency Pt. Pressure   | X = 3.2081,      | Y = -0.9434          |                 |
| Foil Nose Point                   | X = 0.0          | Y = 0.3710           |                 |
| Foil Tail Point                   | X = 3.2434,      | Y = -0.9419          |                 |
| Foil Area (Less Core) = 0.1736    |                  |                      |                 |
| Gaging                            | LAMBDA = 1.4514, | X = 2.4249,          | Y = -0.2678     |
| Gaging Angle                      | = 49.880,        |                      |                 |
| Center of Gravity                 | X = 1.6977,      | Y = -0.0585          |                 |
| Radial Reference                  | X = 1.7483,      | Y = 1.2100           |                 |
| Inlet Angle                       | = 90.000,        | Delta Beta 1 = 0.001 |                 |
| Exit Angle                        | = 47.550,        | Delta Beta 2 = 0.001 |                 |
| Uncovered Turning                 | = 9.654          |                      |                 |
| Constant Section Thickness = .050 |                  |                      |                 |

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TABLE IX  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of 1/8T Section = 9.4531  
Pitch = 1.9799

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.4371

| Percent X                          | Foil X                       | Foil Y Suction            | Foil Y (Circle) |
|------------------------------------|------------------------------|---------------------------|-----------------|
| 0.0                                | 0.0                          | -0.0091                   | -0.0359         |
| 0.01                               | 0.0325                       | -0.0090                   | -0.0090         |
| 0.02                               | 0.0650                       | -0.0091                   | -0.0091         |
| 0.03                               | 0.0975                       | -0.0094                   | -0.0094         |
| 0.04                               | 0.1300                       | -0.0096                   | -0.0096         |
| 0.05                               | 0.1625                       | -0.0100                   | -0.0100         |
| 0.10                               | 0.3250                       | -0.0144                   | -0.0144         |
| 0.15                               | 0.4875                       | -0.0227                   | -0.0227         |
| 0.20                               | 0.6500                       | -0.0346                   | -0.0346         |
| 0.25                               | 0.8125                       | -0.0511                   | -0.0511         |
| 0.30                               | 0.9750                       | -0.0728                   | -0.0728         |
| 0.35                               | 1.1375                       | -0.0999                   | -0.0999         |
| 0.40                               | 1.3000                       | -0.1326                   | -0.1326         |
| 0.45                               | 1.4625                       | -0.1722                   | -0.1722         |
| 0.50                               | 1.6250                       | -0.2185                   | -0.2185         |
| 0.55                               | 1.7875                       | -0.2724                   | -0.2724         |
| 0.60                               | 1.9500                       | -0.3341                   | -0.3341         |
| 0.65                               | 2.1125                       | -0.4043                   | -0.4043         |
| 0.70                               | 2.2750                       | -0.4829                   | -0.4829         |
| 0.75                               | 2.4375                       | -0.5703                   | -0.5703         |
| 0.80                               | 2.6000                       | -0.6666                   | -0.6666         |
| 0.85                               | 2.7625                       | -0.7720                   | -0.7720         |
| 0.90                               | 2.9250                       | -0.8864                   | -0.8864         |
| 0.95                               | 3.0875                       | -1.0096                   | -1.0096         |
| 0.98                               | 3.1850                       | -1.0862                   | -1.0862         |
| 0.99                               | 3.2175                       | -1.1123                   | -1.1123         |
| 1.00                               | 3.2500                       | -1.1415                   | -1.1532         |
| Foil L.E. Circle                   | X = 0.0250,                  | Y = -0.0339,              | R = 0.0250      |
| Foil T.E. Circle                   | X = 3.2250,                  | Y = -1.1532,              | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction     | X = 0.0250,                  | Y = -0.0089               |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0250,                  | Y = -0.0589               |                 |
| Foil T.E. Tangency Pt. Suction     | X = 3.2410,                  | Y = -1.1340               |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 3.2090,                  | Y = -1.1724               |                 |
| Foil Nose Point                    | X = 0.0                      | Y = -0.0339               |                 |
| Foil Tail Point                    | X = 3.2442,                  | Y = -1.1692               |                 |
| Foil Area (Less Core) = 0.1704     |                              |                           |                 |
| Gaging Gaging Angle                | LAMBDA = 1.5786,<br>= 52.877 | X = 2.4368,               | Y = -0.5699     |
| Center of Gravity Radial Reference | X = 1.6908,<br>X = 1.7483,   | Y = -0.3909<br>Y = 1.2100 |                 |
| Inlet Angle                        | = 90.000,                    | Delta Beta 1 = 0.001      |                 |
| Exit Angle                         | = 50.133,                    | Delta Beta 2 = 0.001      |                 |
| Uncovered Turning                  | = 10.405                     |                           |                 |

Constant Section Thickness = .050

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TABLE X  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of 1/4T Section = 9.8437  
Pitch = 2.0617

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.3792

| Percent X                          | Foil X                       | Foil Y Suction            | Foil Y (Circle) |
|------------------------------------|------------------------------|---------------------------|-----------------|
| 0.0                                | 0.0                          | -0.4270                   | -0.4520         |
| 0.01                               | 0.0325                       | -0.4270                   | -0.4270         |
| 0.02                               | 0.0650                       | -0.4271                   | -0.4271         |
| 0.03                               | 0.0975                       | -0.4272                   | -0.4272         |
| 0.04                               | 0.1300                       | -0.4274                   | -0.4274         |
| 0.05                               | 0.1625                       | -0.4277                   | -0.4277         |
| 0.10                               | 0.3250                       | -0.4305                   | -0.4305         |
| 0.15                               | 0.4875                       | -0.4358                   | -0.4358         |
| 0.20                               | 0.6500                       | -0.4439                   | -0.4439         |
| 0.25                               | 0.8125                       | -0.4551                   | -0.4551         |
| 0.30                               | 0.9750                       | -0.4699                   | -0.4699         |
| 0.35                               | 1.1375                       | -0.4889                   | -0.4889         |
| 0.40                               | 1.3000                       | -0.5125                   | -0.5125         |
| 0.45                               | 1.4625                       | -0.5413                   | -0.5413         |
| 0.50                               | 1.6250                       | -0.5761                   | -0.5761         |
| 0.55                               | 1.7875                       | -0.6176                   | -0.6176         |
| 0.60                               | 1.9500                       | -0.6662                   | -0.6662         |
| 0.65                               | 2.1125                       | -0.7228                   | -0.7228         |
| 0.70                               | 2.2750                       | -0.7878                   | -0.7878         |
| 0.75                               | 2.4375                       | -0.8615                   | -0.8615         |
| 0.80                               | 2.6000                       | -0.9443                   | -0.9443         |
| 0.85                               | 2.7625                       | -1.0362                   | -1.0362         |
| 0.90                               | 2.9250                       | -1.1373                   | -1.1373         |
| 0.95                               | 3.0875                       | -1.2477                   | -1.2477         |
| 0.98                               | 3.1850                       | -1.3201                   | -1.3201         |
| 0.99                               | 3.2175                       | -1.3455                   | -1.3455         |
| 1.00                               | 3.2500                       | -1.3676                   | -1.3800         |
| Foil L.E. Circle                   | X = 0.0250,                  | Y = -0.4520,              | R = 0.0250      |
| Foil T.E. Circle                   | X = 3.2250,                  | Y = -1.3800,              | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction     | X = 0.0250,                  | Y = -0.4270               |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0250,                  | Y = -0.4770               |                 |
| Foil T.E. Tangency Pt. Suction     | X = 3.2402,                  | Y = -1.3601               |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 3.2098,                  | Y = -1.3999               |                 |
| Foil Nose Point                    | X = 0.0                      | Y = -0.4520               |                 |
| Foil Tail Point                    | X = 3.2449,                  | Y = -1.3952               |                 |
| Foil Area (Less Core) = 0.1585     |                              |                           |                 |
| Gaging Gaging Angle                | LAMBDA = 1.7072,<br>= 55.900 | X = 2.4622,               | Y = -0.8735     |
| Center of Gravity Radial Reference | X = 1.6891,<br>X = 1.7483,   | Y = -0.7293<br>Y = 1.2100 |                 |
| Inlet Angle                        | = 90.000,                    | Delta Beta 1 = 0.001      |                 |
| Exit Angle                         | = 52.630,                    | Delta Beta 2 = 0.001      |                 |
| Uncovered Turning                  | = 11.264                     |                           |                 |

Constant Section Thickness = .050

TABLE XI  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of 3/8T Section = 10.2343  
Pitch = 2.1435

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.3321

| Percent X                          | Foil X                       | Foil Y Suction            | Foil Y (Circle) |
|------------------------------------|------------------------------|---------------------------|-----------------|
| 0.0                                | 0.0                          | -0.8247                   | -0.8497         |
| 0.01                               | 0.0325                       | -0.8247                   | -0.8247         |
| 0.02                               | 0.0650                       | -0.8248                   | -0.8248         |
| 0.03                               | 0.0975                       | -0.8248                   | -0.8248         |
| 0.04                               | 0.1300                       | -0.8249                   | -0.8249         |
| 0.05                               | 0.1625                       | -0.8251                   | -0.8251         |
| 0.10                               | 0.3250                       | -0.8266                   | -0.8266         |
| 0.15                               | 0.4875                       | -0.8294                   | -0.8294         |
| 0.20                               | 0.6500                       | -0.8340                   | -0.8340         |
| 0.25                               | 0.8125                       | -0.8403                   | -0.8403         |
| 0.30                               | 0.9750                       | -0.8489                   | -0.8489         |
| 0.35                               | 1.1375                       | -0.8602                   | -0.8602         |
| 0.40                               | 1.3000                       | -0.8748                   | -0.8748         |
| 0.45                               | 1.4625                       | -0.8934                   | -0.8934         |
| 0.50                               | 1.6250                       | -0.9166                   | -0.9166         |
| 0.55                               | 1.7875                       | -0.9455                   | -0.9455         |
| 0.60                               | 1.9500                       | -0.9810                   | -0.9810         |
| 0.65                               | 2.1125                       | -1.0244                   | -1.0244         |
| 0.70                               | 2.2750                       | -1.0763                   | -1.0763         |
| 0.75                               | 2.4375                       | -1.1373                   | -1.1373         |
| 0.80                               | 2.6000                       | -1.2074                   | -1.2074         |
| 0.85                               | 2.7625                       | -1.2860                   | -1.2860         |
| 0.90                               | 2.9250                       | -1.3733                   | -1.3733         |
| 0.95                               | 3.0875                       | -1.4697                   | -1.4697         |
| 0.98                               | 3.1850                       | -1.5344                   | -1.5344         |
| 0.99                               | 3.2175                       | -1.5583                   | -1.5583         |
| 1.00                               | 3.2500                       | -1.5769                   | -1.5899         |
| Foil L.E. Circle                   | X = 0.0250,                  | Y = -0.8497,              | R = 0.0250      |
| Foil T.E. Circle                   | X = 3.2250,                  | Y = -1.5899,              | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction     | X = 0.0250,                  | Y = -0.8497,              |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0250,                  | Y = -0.8497,              |                 |
| Foil T.E. Tangency Pt. Suction     | X = 3.2393,                  | Y = -1.5583,              |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 3.2107,                  | Y = -1.5810,              |                 |
| Foil Nose Point                    | X = 0.0                      | Y = -0.8497               |                 |
| Foil Tail Point                    | X = 3.2455,                  | Y = -1.6042               |                 |
| Foil Area (Less Core) =            | C.1670                       |                           |                 |
| Gaging Angle                       | LAMBDA = 1.8386,<br>= 59.065 | X = 2.4970,               | Y = -1.1620     |
| Center of Gravity Radial Reference | X = 1.6843,<br>X = 1.7483,   | Y = -1.0507<br>Y = 1.2100 |                 |
| Inlet Angle                        | = 90.000,                    | Delta Beta 1 = 0.001      |                 |
| Exit Angle                         | = 55.174,                    | Delta Beta 2 = 0.001      |                 |
| Uncovered Turning                  | = 11.840                     |                           |                 |
| Constant Section Thickness =       | .050                         |                           |                 |

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TABLE XII  
REDESIGNED SECOND VANE CASCADE TURNING VANE

Radius of Tip Section = 10.6250  
Pitch = 2.2253

Axial Chord = 3.2500  
No. of Foils = 4.

Actual Chord = 3.2963

| Percent X                         | Foil X           | Foil Y Suction       | Foil Y (Circle) |
|-----------------------------------|------------------|----------------------|-----------------|
| 0.0                               | 0.0              | -1.1953              | -1.2203         |
| 0.01                              | 0.0325           | -1.1953              | -1.1953         |
| 0.02                              | 0.0650           | -1.1953              | -1.1953         |
| 0.03                              | 0.0975           | -1.1953              | -1.1953         |
| 0.04                              | 0.1300           | -1.1954              | -1.1954         |
| 0.05                              | 0.1625           | -1.1954              | -1.1954         |
| 0.10                              | 0.3250           | -1.1959              | -1.1959         |
| 0.15                              | 0.4875           | -1.1969              | -1.1969         |
| 0.20                              | 0.6500           | -1.1985              | -1.1985         |
| 0.25                              | 0.8125           | -1.2008              | -1.2008         |
| 0.30                              | 0.9750           | -1.2041              | -1.2041         |
| 0.35                              | 1.1375           | -1.2087              | -1.2087         |
| 0.40                              | 1.3000           | -1.2150              | -1.2150         |
| 0.45                              | 1.4625           | -1.2238              | -1.2238         |
| 0.50                              | 1.6250           | -1.2358              | -1.2358         |
| 0.55                              | 1.7875           | -1.2523              | -1.2523         |
| 0.60                              | 1.9500           | -1.2751              | -1.2751         |
| 0.65                              | 2.1125           | -1.3057              | -1.3057         |
| 0.70                              | 2.2750           | -1.3456              | -1.3456         |
| 0.75                              | 2.4375           | -1.3952              | -1.3952         |
| 0.80                              | 2.6000           | -1.4534              | -1.4534         |
| 0.85                              | 2.7625           | -1.5191              | -1.5191         |
| 0.90                              | 2.9250           | -1.5917              | -1.5917         |
| 0.95                              | 3.0875           | -1.6726              | -1.6726         |
| 0.98                              | 3.1850           | -1.7288              | -1.7288         |
| 0.99                              | 3.2175           | -1.7544              | -1.7544         |
| 1.00                              | 3.2500           | -1.7662              | -1.7800         |
| Foil L.E. Circle                  | X = 0.0250,      | Y = -1.2203,         | R = 0.0250      |
| Foil T.E. Circle                  | X = 3.2250,      | Y = -1.7800,         | R = 0.0250      |
| Foil L.E. Tangency Pt. Suction    | X = 0.0250,      | Y = -1.1953          |                 |
| Foil L.E. Tangency Pt. Pressure   | X = 0.0250,      | Y = -1.2453          |                 |
| Foil T.E. Tangency Pt. Suction    | X = 3.2383,      | Y = -1.7588          |                 |
| Foil T.E. Tangency Pt. Pressure   | X = 3.2117,      | Y = -1.8012          |                 |
| Foil Nose Point                   | X = 0.0          | Y = -1.2203          |                 |
| Foil Tail Point                   | X = 3.2462,      | Y = -1.7933          |                 |
| Foil Area (Less Core) = 0.1654    |                  |                      |                 |
| Gaging                            | LAMBDA = 1.9724, | X = 2.5401,          | Y = -1.4311     |
| Gaging Angle                      | = 62.420         |                      |                 |
| Center of Gravity                 | X = 1.6735,      | Y = -1.3508          |                 |
| Radial Reference                  | X = 1.7483,      | Y = 1.2100           |                 |
| Inlet Angle                       | = 90.000,        | Delta Beta 1 = 0.000 |                 |
| Exit Angle                        | = 57.790,        | Delta Beta 2 = 0.000 |                 |
| Uncovered Turning                 | = 12.139         |                      |                 |
| Constant Section Thickness = .050 |                  |                      |                 |

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TABLE XIII  
RECONTOURED SECOND VANE

Radius of FF Section = 7.5000  
Pitch = 0.5890

Axial Chord = 0.8320  
No. of Foils = 80.00

Actual Chord = 0.8432

| Percent X                          | Foil X                       | Foil Y Suction             | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|------------------------------------|------------------------------|----------------------------|-----------------|-----------------|-----------------|
| 0.0                                | 0.0                          | -0.2059                    | -0.2011         | -0.1571         | -0.2011         |
| 0.01                               | 0.0083                       | -0.2196                    | -0.2196         | -0.1660         | -0.1862         |
| 0.02                               | 0.0166                       | -0.2329                    | -0.2329         | -0.1750         | -0.1836         |
| 0.03                               | 0.0250                       | -0.2458                    | -0.2458         | -0.1820         | -0.1853         |
| 0.04                               | 0.0333                       | -0.2583                    | -0.2583         | -0.1923         | -0.1923         |
| 0.05                               | 0.0416                       | -0.2705                    | -0.2705         | -0.2010         | -0.2010         |
| 0.10                               | 0.0832                       | -0.3266                    | -0.3266         | -0.2422         | -0.2422         |
| 0.15                               | 0.1248                       | -0.3744                    | -0.3744         | -0.2792         | -0.2792         |
| 0.20                               | 0.1664                       | -0.4143                    | -0.4143         | -0.3111         | -0.3111         |
| 0.25                               | 0.2080                       | -0.4465                    | -0.4465         | -0.3374         | -0.3374         |
| 0.30                               | 0.2496                       | -0.4711                    | -0.4711         | -0.3572         | -0.3572         |
| 0.35                               | 0.2912                       | -0.4882                    | -0.4882         | -0.3699         | -0.3699         |
| 0.40                               | 0.3328                       | -0.4979                    | -0.4979         | -0.3752         | -0.3752         |
| 0.45                               | 0.3744                       | -0.5001                    | -0.5001         | -0.3727         | -0.3727         |
| 0.50                               | 0.4160                       | -0.4950                    | -0.4950         | -0.3627         | -0.3627         |
| 0.55                               | 0.4576                       | -0.4824                    | -0.4824         | -0.3453         | -0.3453         |
| 0.60                               | 0.4992                       | -0.4622                    | -0.4622         | -0.3214         | -0.3214         |
| 0.65                               | 0.5408                       | -0.4344                    | -0.4344         | -0.2914         | -0.2914         |
| 0.70                               | 0.5824                       | -0.3987                    | -0.3987         | -0.2562         | -0.2562         |
| 0.75                               | 0.6240                       | -0.3550                    | -0.3550         | -0.2164         | -0.2164         |
| 0.80                               | 0.6656                       | -0.3028                    | -0.3028         | -0.1728         | -0.1728         |
| 0.85                               | 0.7072                       | -0.2420                    | -0.2420         | -0.1260         | -0.1260         |
| 0.90                               | 0.7488                       | -0.1719                    | -0.1719         | -0.0763         | -0.0763         |
| 0.95                               | 0.7904                       | -0.0922                    | -0.0922         | -0.0244         | -0.0244         |
| 0.98                               | 0.8154                       | -0.0394                    | -0.0394         | 0.0074          | 0.0075          |
| 0.99                               | 0.8237                       | -0.0210                    | -0.0210         | 0.0180          | 0.0099          |
| 1.00                               | 0.8320                       | -0.0022                    | -0.0            | 0.294           | -0.0            |
| Foil L.E. Circle                   | X = 0.0175,                  | Y = -0.2011,               | R = 0.0175      |                 |                 |
| Foil T.E. Circle                   | X = 0.8220,                  | Y = -0.0                   | R = 0.0100      |                 |                 |
| Foil L.E. Tangency Pt. Suction     | X = 0.0026,                  | Y = -0.2102                |                 |                 |                 |
| Foil L.E. Tangency Pt. Pressure    | X = 0.0302,                  | Y = -0.1891                |                 |                 |                 |
| Foil T.E. Tangency Pt. Suction     | X = 0.8312,                  | Y = -0.0040                |                 |                 |                 |
| Foil T.E. Tangency Pt. Pressure    | X = 0.8141,                  | Y = 0.0061                 |                 |                 |                 |
| Foil Nose Point                    | X = 0.0069,                  | Y = -0.1872                |                 |                 |                 |
| Foil Tail Point                    | X = 0.8271,                  | Y = 0.0086                 |                 |                 |                 |
| Foil Area                          | = 0.0920                     |                            |                 |                 |                 |
| Gaging Gaging Angle                | LAMBDA = 0.2941,<br>= 29.950 | X = 0.6024,                | Y = -0.3787     |                 |                 |
| Center of Gravity Radial Reference | X = 0.4301,<br>X = 0.4301,   | Y = -0.3316<br>Y = -0.3316 |                 |                 |                 |
| Inlet Angle                        | = 37.330,                    | DELTA BETA 1 = 12.000      |                 |                 |                 |
| Exit Angle                         | = 30.570,                    | DELTA BETA 2 = 14.000      |                 |                 |                 |
| Uncovered Turning                  | = 20.089                     |                            |                 |                 |                 |
| Min. Moment of Inertia             | = 0.00077115                 |                            |                 |                 |                 |
| Max. Moment of Inertia             | = 0.00450036                 |                            |                 |                 |                 |
| Principal Axis Angle               | = -17.163                    |                            |                 |                 |                 |
| Pitch/Axial Chord                  | = 0.7080                     |                            |                 |                 |                 |
| Pitch/Actual Chord                 | = 0.6986                     |                            |                 |                 |                 |

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## TABLE XIV

### RECONTOURED SECOND VANE

Radius of AA Section = 7.6500  
Pitch = 0.6008

Axial Chord = 0.8357  
No. of Foils = 80.00

Actual Chord = 0.8563

| Percent X | Foil X  | Foil Y Suction | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|-----------|---------|----------------|-----------------|-----------------|-----------------|
| 0.0       | -0.0083 | -0.2334        | -0.2284         | -0.1826         | -0.2284         |
| 0.01      | 0.0001  | -0.2474        | -0.2474         | -0.1916         | -0.2130         |
| 0.02      | 0.0085  | -0.2608        | -0.2608         | -0.2005         | -0.2100         |
| 0.03      | 0.0168  | -0.2739        | -0.2739         | -0.2078         | -0.2112         |
| 0.04      | 0.0252  | -0.2866        | -0.2866         | -0.2175         | -0.2175         |
| 0.05      | 0.0335  | -0.2989        | -0.2989         | -0.2258         | -0.2258         |
| 0.10      | 0.0753  | -0.3547        | -0.3547         | -0.2646         | -0.2646         |
| 0.15      | 0.1171  | -0.4017        | -0.4017         | -0.2983         | -0.2983         |
| 0.20      | 0.1589  | -0.4401        | -0.4401         | -0.3268         | -0.3268         |
| 0.25      | 0.2007  | -0.4703        | -0.4703         | -0.3497         | -0.3497         |
| 0.30      | 0.2425  | -0.4926        | -0.4926         | -0.3665         | -0.3665         |
| 0.35      | 0.2842  | -0.5072        | -0.5072         | -0.3768         | -0.3768         |
| 0.40      | 0.3260  | -0.5143        | -0.5143         | -0.3803         | -0.3803         |
| 0.45      | 0.3678  | -0.5138        | -0.5138         | -0.3768         | -0.3768         |
| 0.50      | 0.4096  | -0.5059        | -0.5059         | -0.3664         | -0.3664         |
| 0.55      | 0.4514  | -0.4904        | -0.4904         | -0.3492         | -0.3492         |
| 0.60      | 0.4932  | -0.4673        | -0.4673         | -0.3254         | -0.3254         |
| 0.65      | 0.5350  | -0.4365        | -0.4365         | -0.2954         | -0.2954         |
| 0.70      | 0.5767  | -0.3977        | -0.3977         | -0.2594         | -0.2594         |
| 0.75      | 0.6185  | -0.3507        | -0.3507         | -0.2182         | -0.2182         |
| 0.80      | 0.6603  | -0.2953        | -0.2953         | -0.1725         | -0.1725         |
| 0.85      | 0.7021  | -0.2316        | -0.2316         | -0.1230         | -0.1230         |
| 0.90      | 0.7439  | -0.1595        | -0.1595         | -0.0702         | -0.0702         |
| 0.95      | 0.7857  | -0.0790        | -0.0790         | -0.0146         | -0.0146         |
| 0.98      | 0.8107  | -0.0267        | -0.0267         | -0.0197         | 0.0195          |
| 0.99      | 0.8191  | -0.0085        | -0.0085         | 0.0311          | 0.0220          |
| 1.00      | 0.8275  | 0.0099         | 0.0121          | 0.0433          | 0.0121          |

Foil L.E. Circle  
Foil T.E. Circle

X = 0.0102,  
X = 0.8175,

Y = -0.2284,  
Y = 0.0121,

R = 0.0185  
R = 0.0100

Foil L.E. Tangency Pt. Suction  
Foil L.E. Tangency Pt. Pressure  
Foil T.E. Tangency Pt. Suction  
Foil T.E. Tangency Pt. Pressure

X = -0.0056,  
X = 0.0234,  
X = 0.8266,  
X = 0.8094,

Y = -0.2379  
Y = -0.2155  
Y = 0.0080  
Y = 0.0180

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Foil Nose Point  
Foil Tail Point

X = -0.0011,  
X = 0.8225,

Y = -0.2138  
Y = 0.0208

Foil Area

= 0.0950

Gaging  
Gaging Angle

LAMBDA = 0.2962,  
29.535

X = 0.5916,

Y = -0.3820

Center of Gravity  
Radial Reference

X = 0.4125  
X = 0.4301,

Y = -0.3438  
Y = -0.3316

Inlet Angle  
Exit Angle  
Uncovered Turning

= 37.732,  
= 30.022,  
= 18.155

DELTA BETA 1 = 13.749  
DELTA BETA 2 = 1.501

Min. Moment of Inertia  
Max. Moment of Inertia

= 0.00077791  
= 0.00472626

Principal Axis Angle

= -19.327

Pitch/Axial Chord  
Pitch/Actual Chord

= 0.7189  
= 0.7016

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TABLE XV  
RECONTOURED SECOND VANE

Radius of BB Section = 8.4863  
Pitch = 0.6665

Axial Chord = 0.8565  
No. of Foils = 80.00

Actual Chord = 0.9464

| Percent X | Foil X  | Foil Y Suction | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|-----------|---------|----------------|-----------------|-----------------|-----------------|
| 0.0       | -0.0543 | -0.3634        | -0.3570         | -0.3074         | -0.3570         |
| 0.01      | -0.0458 | -0.3771        | -0.3771         | -0.3156         | -0.3393         |
| 0.02      | -0.0372 | -0.3903        | -0.3903         | -0.3234         | -0.3352         |
| 0.03      | -0.0286 | -0.4030        | -0.4030         | -0.3307         | -0.3347         |
| 0.04      | -0.0201 | -0.4152        | -0.4152         | -0.3376         | -0.3378         |
| 0.05      | -0.0115 | -0.4270        | -0.4270         | -0.3442         | -0.3442         |
| 0.10      | 0.0313  | -0.4792        | -0.4792         | -0.3719         | -0.3719         |
| 0.15      | 0.0741  | -0.5208        | -0.5208         | -0.3925         | -0.3925         |
| 0.20      | 0.1170  | -0.5526        | -0.5526         | -0.4073         | -0.4073         |
| 0.25      | 0.1598  | -0.5749        | -0.5749         | -0.4168         | -0.4168         |
| 0.30      | 0.2026  | -0.5883        | -0.5883         | -0.4215         | -0.4215         |
| 0.35      | 0.2454  | -0.5931        | -0.5931         | -0.4215         | -0.4215         |
| 0.40      | 0.2883  | -0.5893        | -0.5893         | -0.4168         | -0.4168         |
| 0.45      | 0.3311  | -0.5773        | -0.5773         | -0.4073         | -0.4073         |
| 0.50      | 0.3739  | -0.5571        | -0.5571         | -0.3927         | -0.3927         |
| 0.55      | 0.4167  | -0.5287        | -0.5287         | -0.3722         | -0.3722         |
| 0.60      | 0.4596  | -0.4921        | -0.4921         | -0.3450         | -0.3450         |
| 0.65      | 0.5024  | -0.4472        | -0.4472         | -0.3101         | -0.3101         |
| 0.70      | 0.5452  | -0.3939        | -0.3939         | -0.2671         | -0.2671         |
| 0.75      | 0.5880  | -0.3319        | -0.3319         | -0.2165         | -0.2165         |
| 0.80      | 0.6309  | -0.2616        | -0.2616         | -0.1594         | -0.1594         |
| 0.85      | 0.6737  | -0.1842        | -0.1842         | -0.0968         | -0.0968         |
| 0.90      | 0.7165  | -0.1010        | -0.1010         | -0.0293         | -0.0293         |
| 0.95      | 0.7593  | -0.0134        | -0.0134         | 0.0425          | 0.0425          |
| 0.98      | 0.7850  | 0.0408         | 0.0408          | 0.0874          | 0.0867          |
| 0.99      | 0.7936  | 0.0591         | 0.0591          | 0.1027          | 0.0896          |
| 1.00      | 0.8022  | 0.0775         | 0.0797          | 0.1182          | 0.0797          |

Foil L.E. Circle

X = -0.0318,

Y = -0.3570,

R = 0.0225

Foil T.E. Circle

X = 0.7922,

Y = 0.0797,

R = 0.0100

Foil L.E. Tangency Pt. Suction

X = -0.0509,

Y = -0.3689

Foil L.E. Tangency Pt. Pressure

X = -0.0181,

Y = -0.3392

Foil T.E. Tangency Pt. Suction

X = 0.8012,

Y = 0.0755

Foil T.E. Tangency Pt. Pressure

X = 0.7835,

Y = 0.0846

Foil Nose Point

X = -0.0469,

Y = -0.3403

Foil Tail Point

X = 0.7967,

Y = 0.0886

Foil Area

= 0.1068

Gaging

LAMBDA = 0.3033,

X = 0.5419,

Y = -0.3982

Gaging Angle

= 27.070

Center of Gravity

X = 0.3464,

Y = -0.4008

Radial Reference

X = 0.4301,

Y = -0.3316

Inlet Angle

= 42.100,

DELTA BETA 1 = 20.250

Exit Angle

= 27.170,

DELTA BETA 2 = 4.500

Uncovered Turning

= 12.000

Min. Moment of Inertia

= 0.00079620

Max. Moment of Inertia

= 0.00602193

Principal Axis Angle

= -29.781

Pitch/Axial Chord

= 0.7782

Pitch/Actual Chord

= 0.7042

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TABLE XVI

## RECONTOURED SECOND VANE

Radius of CC Section = 9.4725  
Pitch = 0.7440

Axial Chord = 0.8810  
No. of Foils = 80.00

Actual Chord = 1.0660

| Percent X                       | Foil X           | Foil Y Suction       | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|---------------------------------|------------------|----------------------|-----------------|-----------------|-----------------|
| 0.0                             | -0.1087          | -0.4728              | -0.4641         | -0.4202         | -0.4641         |
| 0.01                            | -0.0999          | -0.4838              | -0.4838         | -0.4259         | -0.4450         |
| 0.02                            | -0.0911          | -0.4945              | -0.4945         | -0.4313         | -0.4402         |
| 0.03                            | -0.0822          | -0.5049              | -0.5049         | -0.4364         | -0.4391         |
| 0.04                            | -0.0734          | -0.5150              | -0.5150         | -0.4412         | -0.4413         |
| 0.05                            | -0.0646          | -0.5247              | -0.5247         | -0.4458         | -0.4458         |
| 0.10                            | -0.0206          | -0.5685              | -0.5685         | -0.4647         | -0.4647         |
| 0.15                            | 0.0235           | -0.6039              | -0.6039         | -0.4778         | -0.4778         |
| 0.20                            | 0.0675           | -0.6304              | -0.6304         | -0.4858         | -0.4858         |
| 0.25                            | 0.1116           | -0.6480              | -0.6480         | -0.4889         | -0.4889         |
| 0.30                            | 0.1556           | -0.6563              | -0.6563         | -0.4872         | -0.4872         |
| 0.35                            | 0.1997           | -0.6552              | -0.6552         | -0.4807         | -0.4807         |
| 0.40                            | 0.2437           | -0.6447              | -0.6447         | -0.4692         | -0.4692         |
| 0.45                            | 0.2878           | -0.6247              | -0.6247         | -0.4521         | -0.4521         |
| 0.50                            | 0.3318           | -0.5952              | -0.5952         | -0.4288         | -0.4288         |
| 0.55                            | 0.3759           | -0.5563              | -0.5563         | -0.3982         | -0.3982         |
| 0.60                            | 0.4199           | -0.5083              | -0.5083         | -0.3592         | -0.3592         |
| 0.65                            | 0.4640           | -0.4513              | -0.4513         | -0.3113         | -0.3113         |
| 0.70                            | 0.5080           | -0.3857              | -0.3857         | -0.2553         | -0.2553         |
| 0.75                            | 0.5521           | -0.3117              | -0.3117         | -0.1922         | -0.1922         |
| 0.80                            | 0.5961           | -0.2299              | -0.2299         | -0.1230         | -0.1230         |
| 0.85                            | 0.6402           | -0.1412              | -0.1412         | -0.0486         | -0.0486         |
| 0.90                            | 0.6842           | -0.0465              | -0.0465         | 0.0307          | 0.0307          |
| 0.95                            | 0.7283           | 0.0533               | 0.0533          | 0.1144          | 0.1144          |
| 0.98                            | 0.7547           | 0.1153               | 0.1153          | 0.1665          | 0.1659          |
| 0.99                            | 0.7635           | 0.1363               | 0.1363          | 0.1843          | 0.1693          |
| 1.00                            | 0.7723           | 0.1574               | 0.1594          | 0.2021          | 0.1594          |
| Foil L.E. Circle                | X = -0.0837,     | Y = -0.4641,         | R = 0.0250      |                 |                 |
| Foil T.E. Circle                | X = 0.7623,      | Y = 0.1594,          | R = 0.0100      |                 |                 |
| Foil L.E. Tangency Pt. Suction  | X = -0.1032,     | Y = -0.4797          |                 |                 |                 |
| Foil L.E. Tangency Pt. Pressure | X = -0.0720,     | Y = -0.4420          |                 |                 |                 |
| Foil T.E. Tangency Pt. Suction  | X = 0.7716,      | Y = 0.1556           |                 |                 |                 |
| Foil T.E. Tangency Pt. Pressure | X = 0.7534,      | Y = 0.1639           |                 |                 |                 |
| Foil Nose Point                 | X = -0.1030,     | Y = -0.4482          |                 |                 |                 |
| Foil Tail Point                 | X = 0.7665,      | Y = 0.1685           |                 |                 |                 |
| Foil Area                       | = 0.1117         |                      |                 |                 |                 |
| Gaging                          | LAMBDA = 0.3115, | X = 0.4937,          | Y = -0.4080     |                 |                 |
| Gaging Angle                    | = 24.750         |                      |                 |                 |                 |
| Center of Gravity               | X = 0.3086,      | Y = -0.4308          |                 |                 |                 |
| Radial Reference                | X = 0.4301,      | Y = -0.3316          |                 |                 |                 |
| Inlet Angle                     | = 50.500,        | DELTA BETA 1 = 3.500 |                 |                 |                 |
| Exit Angle                      | = 24.580,        | DELTA BETA 2 = 4.000 |                 |                 |                 |
| Uncovered Turning               | = 10.674         |                      |                 |                 |                 |
| Min. Moment of Inertia          | = 0.00078028     |                      |                 |                 |                 |
| Max. Moment of Inertia          | = 0.00818481     |                      |                 |                 |                 |
| Principal Axis Angle            | = -38.899        |                      |                 |                 |                 |
| Pitch/Axial Chord               | = 0.8445         |                      |                 |                 |                 |
| Pitch/Actual Chord              | = 0.6979         |                      |                 |                 |                 |

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TABLE XVII

## RECONTOURED SECOND VANE

Radius of DD Section = 10.4600  
Pitch = 0.8215

Axial Chord = 0.9055  
No. of Foils = 80.00

Actual Chord = 1.1749

| Percent X | Foil X  | Foil Y Suction | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|-----------|---------|----------------|-----------------|-----------------|-----------------|
| 0.0       | -0.1631 | -0.5384        | -0.5273         | -0.4868         | -0.5273         |
| 0.01      | -0.1540 | -0.5479        | -0.5479         | -0.4907         | -0.5069         |
| 0.02      | -0.1450 | -0.5570        | -0.5570         | -0.4945         | -0.5015         |
| 0.03      | -0.1359 | -0.5659        | -0.5659         | -0.4980         | -0.4998         |
| 0.04      | -0.1269 | -0.5746        | -0.5746         | -0.5012         | -0.5012         |
| 0.05      | -0.1178 | -0.5829        | -0.5829         | -0.5043         | -0.5043         |
| 0.10      | -0.0725 | -0.6200        | -0.6200         | -0.5164         | -0.5164         |
| 0.15      | -0.0273 | -0.6493        | -0.6493         | -0.5234         | -0.5234         |
| 0.20      | 0.0180  | -0.6702        | -0.6702         | -0.5257         | -0.5257         |
| 0.25      | 0.0633  | -0.6821        | -0.6821         | -0.5232         | -0.5232         |
| 0.30      | 0.1086  | -0.6349        | -0.6849         | -0.5159         | -0.5159         |
| 0.35      | 0.1539  | -0.6781        | -0.6781         | -0.5036         | -0.5036         |
| 0.40      | 0.1991  | -0.6615        | -0.6615         | -0.4857         | -0.4857         |
| 0.45      | 0.2444  | -0.6350        | -0.6350         | -0.4616         | -0.4616         |
| 0.50      | 0.2897  | -0.5984        | -0.5984         | -0.4303         | -0.4303         |
| 0.55      | 0.3350  | -0.5520        | -0.5520         | -0.3905         | -0.3905         |
| 0.60      | 0.3802  | -0.4958        | -0.4958         | -0.3416         | -0.3416         |
| 0.65      | 0.4255  | -0.4303        | -0.4303         | -0.2843         | -0.2843         |
| 0.70      | 0.4708  | -0.3557        | -0.3557         | -0.2194         | -0.2194         |
| 0.75      | 0.5161  | -0.2726        | -0.2726         | -0.1481         | -0.1481         |
| 0.80      | 0.5613  | -0.1819        | -0.1819         | -0.0712         | -0.0712         |
| 0.85      | 0.6066  | -0.0845        | -0.0845         | 0.0109          | 0.0109          |
| 0.90      | 0.6519  | 0.0184         | 0.0184          | 0.0977          | 0.0977          |
| 0.95      | 0.6972  | 0.1260         | 0.1260          | 0.1888          | 0.1888          |
| 0.98      | 0.7243  | 0.1924         | 0.1924          | 0.2455          | 0.2451          |
| 0.99      | 0.7334  | 0.2148         | 0.2148          | 0.2647          | 0.2492          |
| 1.00      | 0.7424  | 0.2373         | 0.2392          | 0.2840          | 0.2392          |

Foil L.E. Circle X = -0.1356, Y = -0.5273, R = 0.0275  
Foil T.E. Circle X = 0.7325, Y = 0.2392, R = 0.0100

Foil L.E. Tangency Pt. Suction X = -0.1554, Y = -0.5464  
Foil L.E. Tangency Pt. Pressure X = -0.1265, Y = -0.5014  
Foil T.E. Tangency Pt. Suction X = 0.7417, Y = 0.2355  
Foil T.E. Tangency Pt. Pressure X = 0.7234, Y = 0.2435

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Foil Nose Point X = -0.1587, Y = -0.5125  
Foil Tail Point X = 0.7365, Y = 0.2484

Foil Area = 0.1166

Gaging LAMBDA = 0.3307, X = 0.4425, Y = -0.4034  
Gaging Angle = 23.739

Center of Gravity X = 0.2691, Y = -0.4297  
Radial Reference X = 0.4301, Y = -0.3316

Inlet Angle = 57.407, DELTA BETA 1 = 26.758  
Exist Angle = 23.599, DELTA BETA 2 = 3.500  
Uncovered Turning = 9.789

Min. Moment of Inertia = 0.00074674  
Max. Moment of Inertia = 0.01048401

Principal Axis Angle = 43.784

Pitch/Axial Chord = 0.9072  
Pitch/Actual Chord = 0.6992

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TABLE XVIII

## RECONTOURED SECOND VANE

Radius of EE Section = 10.8600  
Pitch = 0.8529

Axial Chord = 0.9155  
No. of Foils = 80.00

Actual Chord = 1.1982

| Percent X | Foil X  | Foil Y Suction | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|-----------|---------|----------------|-----------------|-----------------|-----------------|
| 0.0       | -0.1851 | -0.5304        | -0.5179         | -0.4776         | -0.5179         |
| 0.01      | -0.1760 | -0.5387        | -0.5386         | -0.4806         | -0.4973         |
| 0.02      | -0.1668 | -0.5468        | -0.5468         | -0.4845         | -0.4917         |
| 0.03      | -0.1577 | -0.5548        | -0.5548         | -0.4879         | -0.4900         |
| 0.04      | -0.1485 | -0.5625        | -0.5625         | -0.4914         | -0.4914         |
| 0.05      | -0.1393 | -0.5700        | -0.5700         | -0.4944         | -0.4944         |
| 0.10      | -0.0936 | -0.6034        | -0.6034         | -0.5061         | -0.5061         |
| 0.15      | -0.0478 | -0.6301        | -0.6301         | -0.5124         | -0.5124         |
| 0.20      | -0.0020 | -0.6496        | -0.6496         | -0.5135         | -0.5135         |
| 0.25      | 0.0437  | -0.6613        | -0.6613         | -0.5094         | -0.5094         |
| 0.30      | 0.0895  | -0.6648        | -0.6648         | -0.5002         | -0.5002         |
| 0.35      | 0.1353  | -0.6595        | -0.6595         | -0.4855         | -0.4855         |
| 0.40      | 0.1811  | -0.6449        | -0.6449         | -0.4649         | -0.4649         |
| 0.45      | 0.2268  | -0.6207        | -0.6207         | -0.4381         | -0.4381         |
| 0.50      | 0.2726  | -0.5863        | -0.5863         | -0.4041         | -0.4041         |
| 0.55      | 0.3184  | -0.5416        | -0.5416         | -0.3620         | -0.3620         |
| 0.60      | 0.3642  | -0.4866        | -0.4866         | -0.3116         | -0.3116         |
| 0.65      | 0.4099  | -0.4213        | -0.4213         | -0.2535         | -0.2535         |
| 0.70      | 0.4557  | -0.3461        | -0.3461         | -0.1884         | -0.1884         |
| 0.75      | 0.5015  | -0.2615        | -0.2615         | -0.1171         | -0.1171         |
| 0.80      | 0.5473  | -0.1684        | -0.1684         | -0.0402         | -0.0402         |
| 0.85      | 0.5930  | -0.0677        | -0.0677         | 0.0419          | 0.0419          |
| 0.90      | 0.6388  | 0.0395         | 0.0395          | 0.1289          | 0.1289          |
| 0.95      | 0.6846  | 0.1522         | 0.1522          | 0.2204          | 0.2204          |
| 0.98      | 0.7120  | 0.2222         | 0.2222          | 0.2774          | 0.2771          |
| 0.99      | 0.7212  | 0.2459         | 0.2459          | 0.2972          | 0.2815          |
| 1.00      | 0.7303  | 0.2697         | 0.2716          | 0.3161          | 0.2716          |

Foil L.E. Circle X = -0.1572, Y = -0.5179, R = 0.0279  
Foil T.E. Circle X = 0.7203, Y = 0.2716, R = 0.0100

Foil L.E. Tangency Pt. Suction X = -0.1758, Y = -0.5387  
Foil L.E. Tangency Pt. Pressure X = -0.1483, Y = -0.4915  
Foil T.E. Tangency Pt. Suction X = 0.7297, Y = 0.2680  
Foil T.E. Tangency Pt. Pressure X = 0.7113, Y = 0.2759

Foil Nose Point X = -0.1813, Y = -0.5039  
Foil Tail Point X = 0.7243, Y = 0.2807

Foil Area = 0.1242

Gaging LAMBDA = 0.3378, X = 0.4248, Y = 0.3980  
Gaging Angle = 23.334

Center of Gravity X = 0.2674, Y = -0.3990  
Radial Reference X = 0.4301, Y = -0.3316

Inlet Angle = 59.762, DELTA BETA 1 = 23.045  
Exit Angle = 23.247, DELTA BETA 2 = 4.366  
Uncovered Turning = 10.844

Min. Moment of Inertia = 0.00078773  
Max. Moment of Inertia = 0.01155412

Principal Axis Angle = -44.493

Pitch/Axial Chord = 0.9317  
Pitch/Actual Chord = 0.7118

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## TABLE XIX

### RECONTOURED SECOND VANE

|                                 |                      |                       |                    |                    |                    |
|---------------------------------|----------------------|-----------------------|--------------------|--------------------|--------------------|
| Radius of GG Section = 11.4450  | Axial Chord = 0.9300 | Actual Chord = 1.2024 |                    |                    |                    |
| Pitch = 0.8989                  | No. of Foils - 80.00 |                       |                    |                    |                    |
| Percent T<br>X                  | Foil X               | Foil Y<br>Suction     | Foil Y<br>(Circle) | Foil Y<br>Pressure | Foil Y<br>(Circle) |
| 0.0                             | -0.2173              | -0.4729               | -0.4577            | -0.4169            | -0.4577            |
| 0.01                            | -0.2080              | -0.4783               | -0.4783            | -0.4182            | -0.4370            |
| 0.02                            | -0.1987              | -0.4845               | -0.4845            | -0.4232            | -0.4316            |
| 0.03                            | -0.1894              | -0.4902               | -0.4902            | -0.4272            | -0.4302            |
| 0.04                            | -0.1801              | -0.4959               | -0.4959            | -0.4319            | -0.4319            |
| 0.05                            | -0.1708              | -0.5014               | -0.5014            | -0.4356            | -0.4356            |
| 0.10                            | -0.1243              | -0.5274               | -0.5274            | -0.4500            | -0.4500            |
| 0.15                            | -0.0778              | -0.5502               | -0.5502            | -0.4579            | -0.4579            |
| 0.20                            | -0.0313              | -0.5693               | -0.5693            | -0.4593            | -0.4593            |
| 0.25                            | 0.0152               | -0.5839               | -0.5839            | -0.4542            | -0.4542            |
| 0.30                            | 0.0617               | -0.5931               | -0.5931            | -0.4426            | -0.4426            |
| 0.35                            | 0.1082               | -0.5958               | -0.5958            | -0.4244            | -0.4244            |
| 0.40                            | 0.1547               | -0.5910               | -0.5910            | -0.3999            | -0.3999            |
| 0.45                            | 0.2012               | -0.5773               | -0.5773            | -0.3689            | -0.3689            |
| 0.50                            | 0.2477               | -0.5534               | -0.5534            | -0.3317            | -0.3317            |
| 0.55                            | 0.2941               | -0.5182               | -0.5182            | -0.2882            | -0.2882            |
| 0.60                            | 0.3407               | -0.4710               | -0.4710            | -0.2387            | -0.2387            |
| 0.65                            | 0.3872               | -0.4112               | -0.4112            | -0.1831            | -0.1831            |
| 0.70                            | 0.4337               | -0.3391               | -0.3391            | -0.1217            | -0.1217            |
| 0.75                            | 0.4802               | -0.2553               | -0.2553            | -0.0545            | -0.0545            |
| 0.80                            | 0.5267               | -0.1602               | -0.1602            | 0.0182             | 0.0182             |
| 0.85                            | 0.5731               | -0.0548               | -0.0548            | 0.0964             | 0.0964             |
| 0.90                            | 0.6197               | 0.0604                | 0.0604             | 0.1799             | 0.1799             |
| 0.95                            | 0.6662               | 0.1846                | 0.1846             | 0.2685             | 0.2685             |
| 0.98                            | 0.6941               | 0.2632                | 0.2632             | 0.3239             | 0.3239             |
| 0.99                            | 0.7034               | 0.2900                | 0.2900             | 0.3448             | 0.3288             |
| 1.00                            | 0.7127               | 0.3171                | 0.3188             | 0.3616             | 0.3188             |
| Foil L.E. Circle                | X = -0.1898,         | Y = -0.4577,          | R = 0.0275         |                    |                    |
| Foil T.E. Circle                | X = 0.7027,          | Y = 0.3188,           | R = 0.0100         |                    |                    |
| Foil L.E. Tangency Pt. Suction  | X = -0.2045,         | Y = -0.4810           |                    |                    |                    |
| Foil L.E. Tangency Pt. Pressure | X = -0.1795,         | Y = -0.4322           |                    |                    |                    |
| Foil T.E. Tangency Pt. Suction  | X = 0.7121,          | Y = 0.3156            |                    |                    |                    |
| Foil T.E. Tangency Pt. Pressure | X = 0.6937,          | Y = 0.3233            |                    |                    |                    |
| Foil Nose Point                 | X = -0.2143,         | Y = -0.4451           |                    |                    |                    |
| Foil Tail Point                 | X = 0.7065,          | Y = 0.3281            |                    |                    |                    |
| Foil Area                       | = 0.1438             |                       |                    |                    |                    |
| Gaging                          | LAMBDA = 0.3459,     | X = 0.4050,           | Y = -0.3849        |                    |                    |
| Gaging Angle                    | = 22.630             |                       |                    |                    |                    |
| Center of Gravity               | X = 0.2813,          | Y = -0.3210           |                    |                    |                    |
| Radial Reference                | X = 0.4301,          | Y = -0.3316           |                    |                    |                    |
| Inlet Angle                     | = 62.900,            | DELTA BETA 1 = 10.000 |                    |                    |                    |
| Exit Angle                      | = 22.570,            | DELTA BETA 2 = 7.500  |                    |                    |                    |
| Uncovered Turning               | = 14.51              |                       |                    |                    |                    |
| Min. Moment of Inertia          | = 0.00095658         |                       |                    |                    |                    |
| Max. Moment of Inertia          | = 0.01280395         |                       |                    |                    |                    |
| Principal Axis Angle            | = -44.549            |                       |                    |                    |                    |
| Pitch/Axial Chord               | = 0.9665             |                       |                    |                    |                    |
| Pitch/Actual Chord              | = 0.7476             |                       |                    |                    |                    |

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TABLE XX  
RECONTOURED SECOND VANE

Radius of HH Section = 11.4100  
Pitch = 0.8961

Axial Chord = 0.9291  
No. of Foils = 80.00

Actual Chord = 1.2031

| Percent X | Foil X  | Foil Y Suction | Foil Y (Circle) | Foil Y Pressure | Foil Y (Circle) |
|-----------|---------|----------------|-----------------|-----------------|-----------------|
| 0.0       | -0.2154 | -0.4778        | -0.4628         | -0.4221         | -0.4628         |
| 0.01      | -0.2061 | -0.4835        | -0.4835         | -0.4235         | -0.4422         |
| 0.02      | -0.1968 | -0.4898        | -0.4898         | -0.4284         | -0.4368         |
| 0.03      | -0.1875 | -0.4957        | -0.4957         | -0.4323         | -0.4353         |
| 0.04      | -0.1783 | -0.5015        | -0.5015         | -0.4370         | -0.4370         |
| 0.05      | -0.1690 | -0.5072        | -0.5072         | -0.4406         | -0.4406         |
| 0.10      | -0.1225 | -0.5337        | -0.5337         | -0.4547         | -0.4547         |
| 0.15      | -0.0761 | -0.5568        | -0.5568         | -0.4625         | -0.4625         |
| 0.20      | -0.0296 | -0.5758        | -0.5758         | -0.4638         | -0.4638         |
| 0.25      | 0.0169  | -0.5901        | -0.5901         | -0.4587         | -0.4587         |
| 0.30      | 0.0633  | -0.5988        | -0.5988         | -0.4472         | -0.4472         |
| 0.35      | 0.1098  | -0.6009        | -0.6009         | -0.4293         | -0.4293         |
| 0.40      | 0.1562  | -0.5952        | -0.5952         | -0.4050         | -0.4050         |
| 0.45      | 0.2027  | -0.5806        | -0.5806         | -0.3743         | -0.3743         |
| 0.50      | 0.2491  | -0.5559        | -0.5559         | -0.3372         | -0.3372         |
| 0.55      | 0.2956  | -0.5199        | -0.5199         | -0.2938         | -0.2938         |
| 0.60      | 0.3421  | -0.4720        | -0.4720         | -0.2440         | -0.2440         |
| 0.65      | 0.3885  | -0.4117        | -0.4117         | -0.1882         | -0.1882         |
| 0.70      | 0.4350  | -0.3393        | -0.3393         | -0.1264         | -0.1264         |
| 0.75      | 0.4814  | -0.2553        | -0.2553         | -0.0589         | -0.0589         |
| 0.80      | 0.5279  | -0.1603        | -0.1603         | 0.0143          | 0.0143          |
| 0.85      | 0.5743  | -0.0552        | -0.0552         | 0.0928          | 0.0928          |
| 0.90      | 0.6208  | 0.0595         | 0.0595          | 0.1766          | 0.1766          |
| 0.95      | 0.6673  | 0.1829         | 0.1829          | 0.2655          | 0.2655          |
| 0.98      | 0.6951  | 0.2608         | 0.2608          | 0.3212          | 0.3211          |
| 0.99      | 0.7044  | 0.2874         | 0.2874          | 0.3420          | 0.3260          |
| 1.00      | 0.7137  | 0.3143         | 0.3160          | 0.3590          | 0.3160          |

Foil L.E. Circle X = -0.1879, Y = -0.4628, R = 0.0276  
Foil T.E. Circle X = 0.7037, Y = 0.3160, R = 0.0100

Foil L.E. Tangency Pt. Suction X = -0.2028, Y = -0.4860  
Foil L.E. Tangency Pt. Pressure X = -0.1776, Y = -0.4372  
Foil T.E. Tangency Pt. Suction X = 0.7132, Y = 0.3128  
Foil T.E. Tangency Pt. Pressure X = 0.6947, Y = 0.3204

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Foil Nose Point X = -0.2124, Y = -0.4502  
Foil Tail Point X = 0.7076, Y = 0.3252

Foil Area = 0.1423

Gaging LAMBDA = 0.3455, X = 0.4061, Y = -0.3857  
Gaging Angle = 22.676

Center of Gravity X = 0.2801, Y = -0.3265  
Radial Reference X = 0.4301, Y = -0.3316

Inlet Angle = 62.722, DELTA BETA 1 = 11.047  
Exit Angle = 22.616, DELTA BETA 2 = 7.249  
Uncovered Turning = 14.210

Min. Moment of Inertia = 0.00094165  
Max. Moment of Inertia = 0.01275547

Principal Axis Angle = -44.566

Pitch/Axial Chord = 0.9645  
Pitch/Actual Chord = 0.7448

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REFERENCES

1. H. Welna, D. E. Dahlberg and W. H. Heiser; (Unclassified title) Investigation of a Highly Loaded Two-Stage Fan-Drive Turbine; Technical Report, AFAPL-TR-69-92 Volume 1; Pratt & Whitney Aircraft Division of United Aircraft Corporation; June 1968; Confidential.
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|   | ROLE   | WT | ROLE   | WT | ROLE   | WT |
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78