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DESIGN OF A COMPACT PLENUM CHAMBER FOR SUPPLY OF AIR TO AN ANNULAR SPACE WITH LOW ENERGY LOSSES

by

D.A. Bayly

PCN 21K01

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ABSTRACT

This report describes the design of a compact plenum chamber the function of which is to receive air from a rectangular duct and deliver it to an annular space with low energy losses. Turning vanes formed from a single thickness of sheet steel ensure that air leaves the chamber essentially perpendicular to the plane of the annulus. A FORTRAN program is presented which plots the two dimensional development of the turning vane.

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DESIGN OF A COMPACT PLENUM CHAMBER FOR SUPPLY OF AIR TO AN ANNULAR SPACE WITH LOW ENERGY LOSSES (U)

by

D.A. Bayly

1. INTRODUCTION

This report describes the design of an air supply manifold for the film cooling facility at the Defence Research Establishment Suffield (DRES). The manifold was required to receive air from a rectangular duct and deliver it to an annular space with lower energy losses than had been experienced with previous manifolds. Ideally, velocity vectors would be perpendicular to the plane of the annulus and uniform in magnitude; however, devices downstream of the annulus could be used to smooth out the velocity profile. The essence of the problem was to move air efficiently through what added up to be a 90 degree turn.

Figure 1 shows the DRES Film Cooling Facility. The Orenda 8 turbojet engine draws air through an intake on the south side of the building and expels hot exhaust gases into the exhaust duct on the north side of the building. Excess gas is diverted by the continuously adjustable bypass unit. After the bypass the exhaust flows through 24 feet of 2-foot inside diameter pipe to the film cooled test section which is approximately 2 feet in diameter by 2 feet in length. The 15 HP centrifugal fan drives air through approximately 40 feet of 20-inch diameter duct, and the manifold, to the test section. Convective heat transfer from the hot exhaust gas to the walls of the test section is reduced by the film of cool air.

Figure 2 shows the original manifold, called Manifold I, with tangential and radial air entry, and the improved Manifold II. The film cooled test section and cooling air duct are shown in phantom lines. It was found that systems using Manifold I had unsatisfactory total cooling air flow and velocity distribution in the test section. Efficiency of the air supply system was defined as P_v/P_{FT} where P_v is velocity pressure at the annulus and P_{FT} is the fan total pressure. This ratio was experimentally determined to be 4 - 28% for various systems using Manifold I. Data revealed that Manifold I was the largest source of inefficiency in the air supply system. Redesign of the manifold had the greatest potential for improvement of efficiency.

A lower entry velocity and more streamlined interior would reduce turbulent losses. Tangential velocity components at the annular exit of Manifold I were not good for film cooling and it would be advantageous to convert them into axial velocity components. These guidelines were followed in the design of Manifold II.

2. APPROACH

Two approaches were considered. First, a large plenum chamber could be used. The path of the air from entry to outlet of the chamber would not be known precisely but, because of low velocities, low resistance and good distribution could be expected. Second, the manifold could be compact and direct relatively high speed flows over streamlined surfaces. It was not known what size of large plenum chamber was necessary. Support posts for the exhaust duct in the film cooling facility would interfere with any large chamber. Therefore, it was decided to build a compact, streamlined manifold.

3. FEATURES

Figure 3 shows the general arrangement of Manifold II. Further detail is contained in Figures 4 and 5. The inner shell is made from sheet steel to withstand high exhaust gas temperatures. The outer shell is made from plywood for ease of fabrication. Temperatures occurring in the outer shell are quite low. A layer of fiberglas over the plywood adds strength.

The cross-sectional area of the air inlet is 144 square inches, compared to 64 square inches for Manifold I tangential entry and 91 square inches for Manifold I radial entry. The air inlet velocity to Manifold II is therefore lower than to either of the Manifold I variations.

Between inner and outer shells of Manifold II is a trapezoidal passage (Figure 5) the cross-sectional area of which decreases proportionally to the angle travelled around the manifold. Constant velocity is maintained in the trapezoidal passage by decreasing area as air bleeds off to the turning vanes and test section. The function of the turning vanes is to eliminate tangential velocity components. All the vanes are identical in design because velocity in the trapezoidal passage is constant.

The inner shell shown in Figure 5 is conical so that most of the manifold is separated from the exhaust pipe by fiberglas insulation and/or air space. Width of the turning vane trailing edge is fixed by choice of the maximum slot width for the film cooled test section. Preliminary calculations showed that if the width of the vane was the same at the leading edge as at the trailing edge, the effective cross-sectional area between the vanes at the trailing edge would be 3.28 times that at the leading edge. When the walls of a diffuser diverge too quickly, air flow tends to separate from the walls. Flow separation will also occur on the inner surface of an elbow. The passage between vanes, as shown in Figure 3, is both a diffuser and and elbow. Thus the ideal uniform velocity profile at the exit from the vane passage is unlikely to be achieved. There will be a region of low velocity near the "inner" vane and a region of high velocity near the "outer" vane. Increasing the width of the vane leading edge would tend to relieve the velocity profile problem because it would make the passage less divergent. However, another factor complicates the situation. Figure 5 shows that after leaving the vane passage, the air must make another slight turn to flow parallel to the test section wall. Increasing the width of the vane leading edge would increase the average angle through which the air would have to turn when leaving the vane passage. A compromise leading edge width was chosen so that the previously mentioned area ratio became 2.68 and the turning angle at vane exit was 19 degrees.

4. TURNING VANES

Airfoil shaped vanes would be most desirable but casting or forging facilities were not readily available. Vanes were bent from single thicknesses of sheet steel.

Cylindrical and rectilinear coordinates are defined in Figure 6. The theoretical surface of the vane is generated by a radial line segment, the generatrix, simultaneously rotating in the θ direction and translating in the z-direction. Intersections with conical surfaces form the inner and outer edges of the vane.

Energy losses due to turbulence are minimized by ensuring that the tangent plane to the vane leading edge is coplanar with the velocity vector of the air leaving the trapezoidal passage (Figure 7). V is the velocity vector of the air at the vane leading edge. V_t, V_a and V_r are its tangential, axial, and radial components respectively. In order that the leading edge tangent plane be coplanar with V, the angle β must equal $\tan^{-1}\left[\frac{V_a}{V_t}\right]$.

Figure 8 illustrates some of the quantities used in the calculation of V_a and V_t. Volume flow rate into the manifold through A_0 equals volume flow rate out of the manifold through A_1 assuming constant air density and no leaks.

$$V_a = \frac{Q}{\pi(r_{10}^2 - r_1^2)}$$

By the principle of conservation of angular momentum, the product of radius times tangential velocity is constant, neglecting change in momentum due to friction and turbulence losses; hence V_t at the mean radius of the vane leading edge is estimated as

$$V_t = \frac{Q}{A_0} \frac{r_0}{\left(\frac{r_1 + r_{10}}{2}\right)} .$$

Thus $$\beta = \tan^{-1}\left[\frac{V_a}{V_t}\right] = \tan^{-1}\left[\frac{A_0(r_1 + r_{10})}{2\pi(r_{10}^2 - r_1^2)r_0}\right] .$$

Note that β depends only on the geometry of the manifold and does not vary with flow rate. Using average values of radius and velocity results in small errors for points on the vane leading edge other than the midpoint.

The orientation of the leading edge tangent plane is now known, and the trailing edge tangent plane must be coplanar with the z axis. The scheme chosen to describe the curved surface joining the two tangent planes is a curve of z versus the $\bar{r}\theta$ product as constructed in Figure 9. $\bar{r} = \frac{(r_1 + r_{10})}{2}$. From the curve is obtained a set of (θ, z) pairs.

Next, r values are attached to the (θ, z) pairs for points on the inner and outer edges of the vane. These edges are the intersection of the vane with conical surfaces. See Figure 10. For the inner edge,

$$r = r_1 - \frac{z}{z_9} (r_1 - r_9)$$

and for the outer edge

$$r = r_{10} - \frac{z}{z_9} (r_{10} - r_{18}).$$

As explained by Reference 1, the vane is a warped surface which cannot be developed on a plane. It is necessary to approximate the warped surface with a series of triangles so the vane can be laid out on a flat sheet. Figure 11 illustrates the three-dimensional vane and its two-dimensional pattern. Points 1 to 18 lie on the theoretical inner and outer edges of the vane and their (r, θ, z) coordinates are known. The lengths of all the line segments are claculated using the Pythagorean theorem for three dimensions.

The flat layout is started with segment 1-10 along the y-axis. Arcs having the lenths of segments 1-11 and 10-11 could be struck from points 1 and 10 respectively to locate point 11. Alternatively, the angle between segments 1-10 and 1-11 could be calculated using the law of cosines, and then point 11 located trigonometrically. The latter method lends itself to computer programming. Point 2 is located after point 11, then point 12 and so on.

A quadrilateral 9-19-20-18 is added to the vane coplanar with the z-axis to help establish flow in that direction. Point 19 is separated 1/4 inch from the inner cone to reduce heat transfer and problems due to thermal expansion.

A FORTRAN program was written following the methods outlined above to calculate coordinates and plot a two-dimensional vane pattern. It requires as input the (θ, z) coordinates of points 1 to 18 inclusive, and the set of point-number pairs for the end points of line segments. The variable definitions and program listing are included as Appendix A, while the full scale vane pattern is shown in Figure 12. Note that the pattern has been reflected about the x-axis because the tangential velocity in the actual manifold is opposite to that imagined for the development of the equations describing the vane. Another FORTRAN program, not included here, plotted the lines of contact of the vane on the inner and outer conical surfaces. These lines aided construction of a three-dimensional vane model, and assembly of the vanes on the conical surfaces.

5. CONCLUSION

Efficiency $\frac{P_v}{P_{FT}}$ of the cooling air system using Manifold II was 0.52 compared to 0.28 for systems using Manifold I. Thus the major objective of the design was achieved. The velocity profile had irregularities in direction and magnitude, but, as previously mentioned, devices downstream of the manifold tended to smooth out the profile.

6. REFERENCE

1. Giesecke et al., Engineering Graphics, Macmillan, 1969.

APPENDIX A

FORTRAN PROGRAM TO PLOT TURNING VANE PATTERN

Variable	Definition	Mode	Class
R(N)	radius r to point N (inches)	real	1
TTA(N)	angle θ to point N (degrees)	"	"
Z(N)	height z of point N (inches)	"	"
ALONG (L)	length of line segment L (inches)	"	"
X(N)	x-coordinate of point N in plot	"	"
Y(N)	y-coordinate of point N in plot	"	"
N	point index number	integer	0
L	line segment index number	"	"
N1	point number at beginning of line segment L	"	"
N2	point number at end of line segment L	"	"
ALPHA	angle of line segment L from reference line 1-10 (degrees)	real	"
J	vertex angle index number	integer	"
C	cosine of vertex angle V	real	"
V	vertex angle between two line segments (degrees)	"	"
B	variable to indicate whether J is even or odd	"	"
AB	smaller angle between line segment 9-18 and y-axis (degrees)	"	"
I	index number used to set order of plotting of line segments	integer	"
D	variable to indicate whether I is even or odd	real	"
XX	x-coordinate of final pen position	"	"

```
C
C        TURNING VANE COMPOSED OF TRIANGULAR ELEMENTS
C                  DRESMES        D.A. BAYLY
C                           THIRD VERSION
C             FULL SCALE PATTERN OF MANIFOLD II VANES
C
      DIMENSION R(18),TTA(18),Z(18),ALONG(33),X(20),Y(20)
C
C
C     READING SET OF (TTA,Z) PAIRS
C
      DO 9 N = 1,18,1
      READ(2,100) TTA(N),Z(N)
  100 FORMAT (5X,F4.1,5X,F5.3)
    9 TTA(N) = TTA(N)*3.141593/180.
C
C
C     CALCULATING R FOR (R,TTA,Z) COORDINATES
C
      DO 10 N = 1,9,1
   10 R(N) = 13.568 - .2516*Z(N)
      DO 20 N = 10,18,1
   20 R(N) = 16.625 - .4440*Z(N)
      DO 30 L = 1,33,1
C
C
C     READING POINT NUMBERS FOR END POINTS OF LINE SEGMENTS
C
      READ(2,101) N1,N2
  101 FORMAT(5X,I3,5X,I3)
C
C
C     CALCULATING LENGTH OF LINE SEGMENT
C
   30 ALONG(L) = SQRT(     (   R(N2)*COS(TTA(N2)) - R(N1)*COS(TTA(N1))   )
     1 **2.    +     (  R(N2)*SIN(TTA(N2)) - R(N1)*SIN(TTA(N1))   ) **2.
     2   +    (   Z(N2) - Z(N1)   )**2.       )
C
C
C     DEFINING (X,Y) COORDINATES OF FIRST TWO POINTS
C
      X(1) = 0.
      Y(1) = 3.057
      X(10) = 0.
      Y(10) = 0.
C
C
C     CALCULATING VERTEX ANGLE BETWEEN SEGMENTS , AND
```

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```
C       (X,Y) COORDINATES OF NEXT POINT
C
        ALPHA = 0.
        DO 40 J = 1,16,1
        C = (  (ALONG(2*J))**2.  -  (ALONG(2 *J+1))**2.  -  (ALONG(2*J-1))
      1  **2.   )    /     ( -2.*(ALONG(2*J+1))*ALONG(2*J-1))
        IF (C) 34,35,35
   34   V = 3.141593 + ATAN ((SQRT(1. - C*C))/C)
        GO TO 36
   35   V = ATAN ((SQRT(1. - C*C))/C)
   36   B = (-1.)**J
        IF(B) 37,37,38
   37   N = (J+21) / 2
        X(N) = X(N-10) + (ALONG(2*J+1))*SIN(V-ALPHA)
        Y(N) = Y(N-10) - (ALONG(2*J+1)) *COS(V-ALPHA)
        GO TO 40
   38   N = (J+2)/2
        X(N) = X(N+9) + (ALONG(2*J+1))*SIN(V-ALPHA)
        Y(N) = Y(N+9) + (ALONG(2*J+1))*COS(V-ALPHA)
   40   ALPHA = V - ALPHA
C
C
C       CALCULATING (X,Y) COORDINATES OF POINTS 19 AND 20
C
   41   AB = ATAN( (X(18)-X(9))/(Y(9)-Y(18)) )
        X(20) = X(18) + 2.188*SIN(1.1529-AB)
        Y(20) = Y(18) + 2.188*COS(1.1529-AB)
        X(19) = X(20) - 1.711*SIN(AB)
        Y(19) = Y(20) + 1.711*COS(AB)
C
C
C       PATTERN REFLECTED AND TRANSLATED
C
        DO 46 N = 1,20,1
   46   Y(N) = 8.  - Y(N)
C
C
C       PLOTTING BEGINS
C
        CALL SCALF (1.0,1.0,0.,0.)
        CALL FPLOT (-2,X(10),Y(10))
        DO 60 N = 1,9,1
        CALL FPLOT(0,X(N),Y(N))
   60   CALL POINT(0)
   61   CALL FPLOT (0,X(19),Y(19))
        CALL POINT(0)
        CALL FPLOT (0,X(20),Y(20))
        CALL POINT(0)
        DO 70 I = 1,9,1
```

```
      N = 19-I
      CALL FPLOT(0,X(N),Y(N))
   70 CALL POINT(0)
      CALL FPLOT(0,X(1),Y(1))
      DO 80 I = 1,16,1
      D = (-1.)**I
      IF(D) 71,71,72
   71 N = 11 + (I-1)/2
      GO TO 80
   72 N = (I + 2)/2
   80 CALL FPLOT(0,X(N),Y(N))
      XX = X(20) +2.
      CALL FPLOT (1,XX,0.)
      CALL EXIT
      END
```


DATA

N	TTA (Degrees)	Z (Inches)
1	0.	0.
2	2.	.175
3	4.	.380
4	6.	.625
5	8.	.920
6	10.	1.295
7	12.	1.820
8	14.	2.670
9	15.	4.000
10	0.	0.
11	1.	.085
12	3.	.275
13	5.	.495
14	7.	.770
15	9.	1.095
16	11.	1.540
17	13.	2.175
18	15.	4.000

L	N1	N2
1	1	10
2	10	11
3	1	11
4	1	2
5	2	11
6	11	12
7	2	12
8	2	3
9	3	12
10	12	13
11	3	13
12	3	4
13	4	13
14	13	14
15	4	14
16	4	5
17	5	14
18	14	15
19	5	15
20	5	6
21	6	15
22	15	16
23	6	16
24	6	7
25	7	16
26	16	17
27	7	17
28	7	8
29	8	17
30	17	18
31	8	18
32	8	9
33	9	18

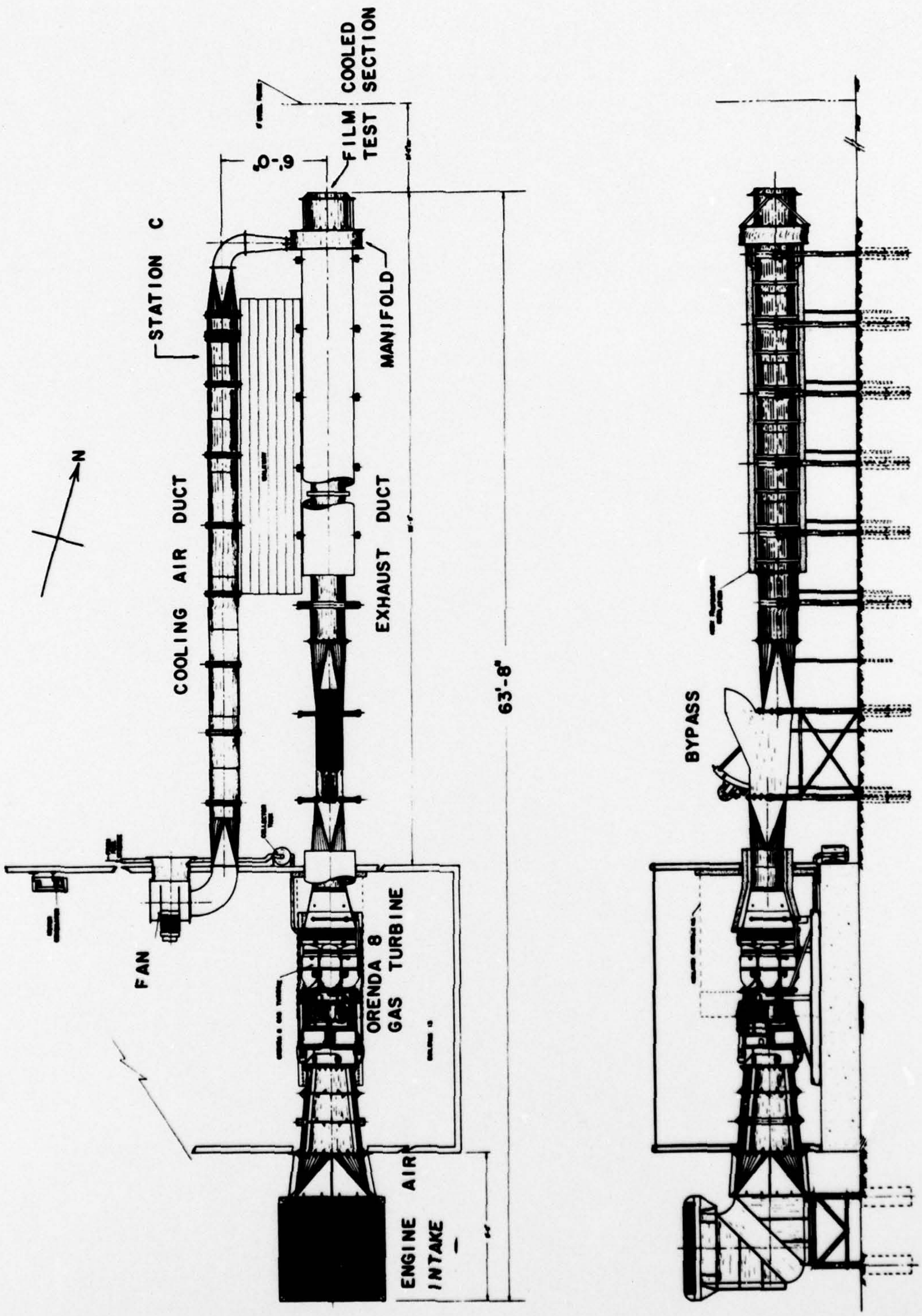

FIG. 1 FILM COOLING FACILITY

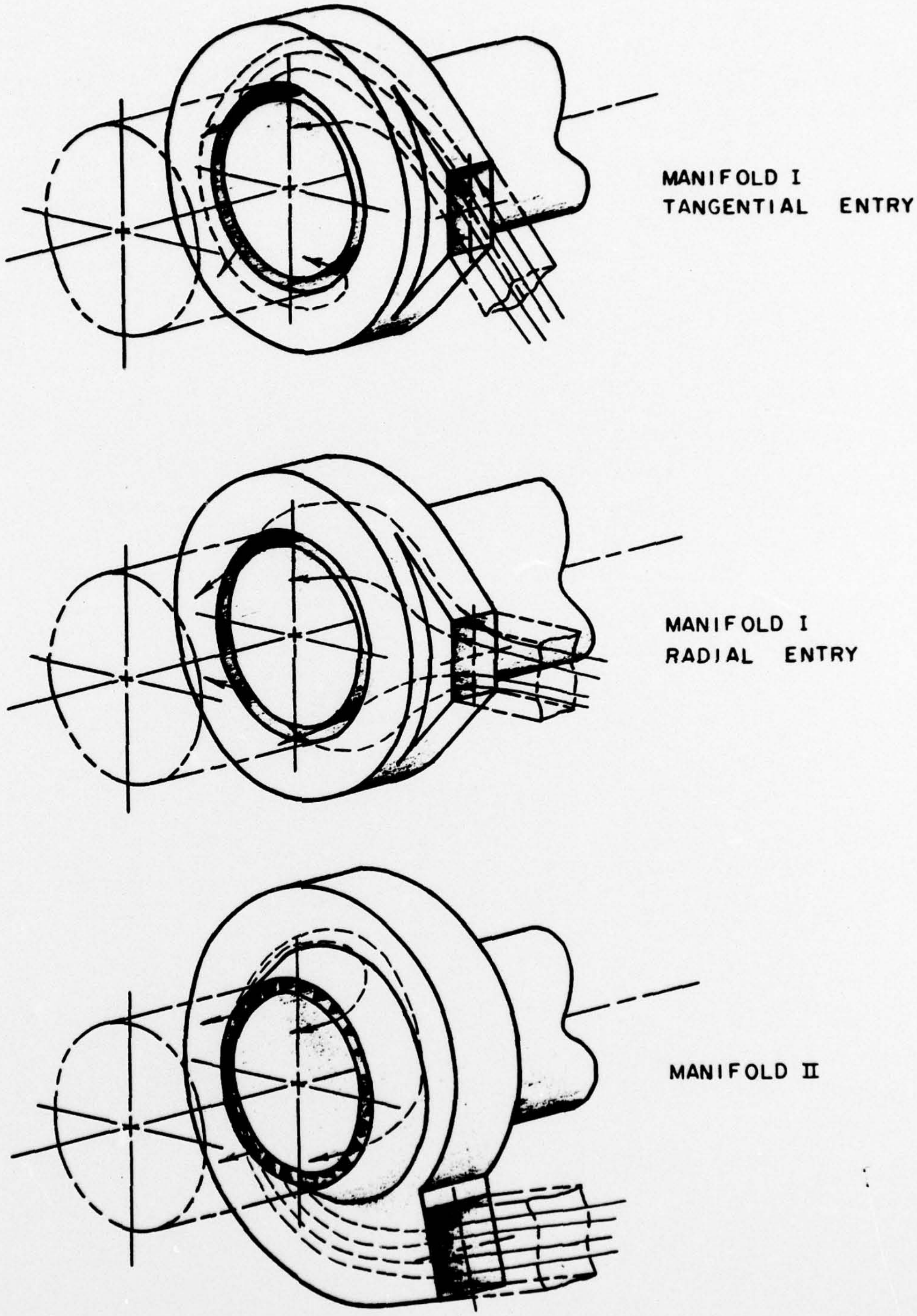

FIG. 2: MANIFOLD VARIATIONS

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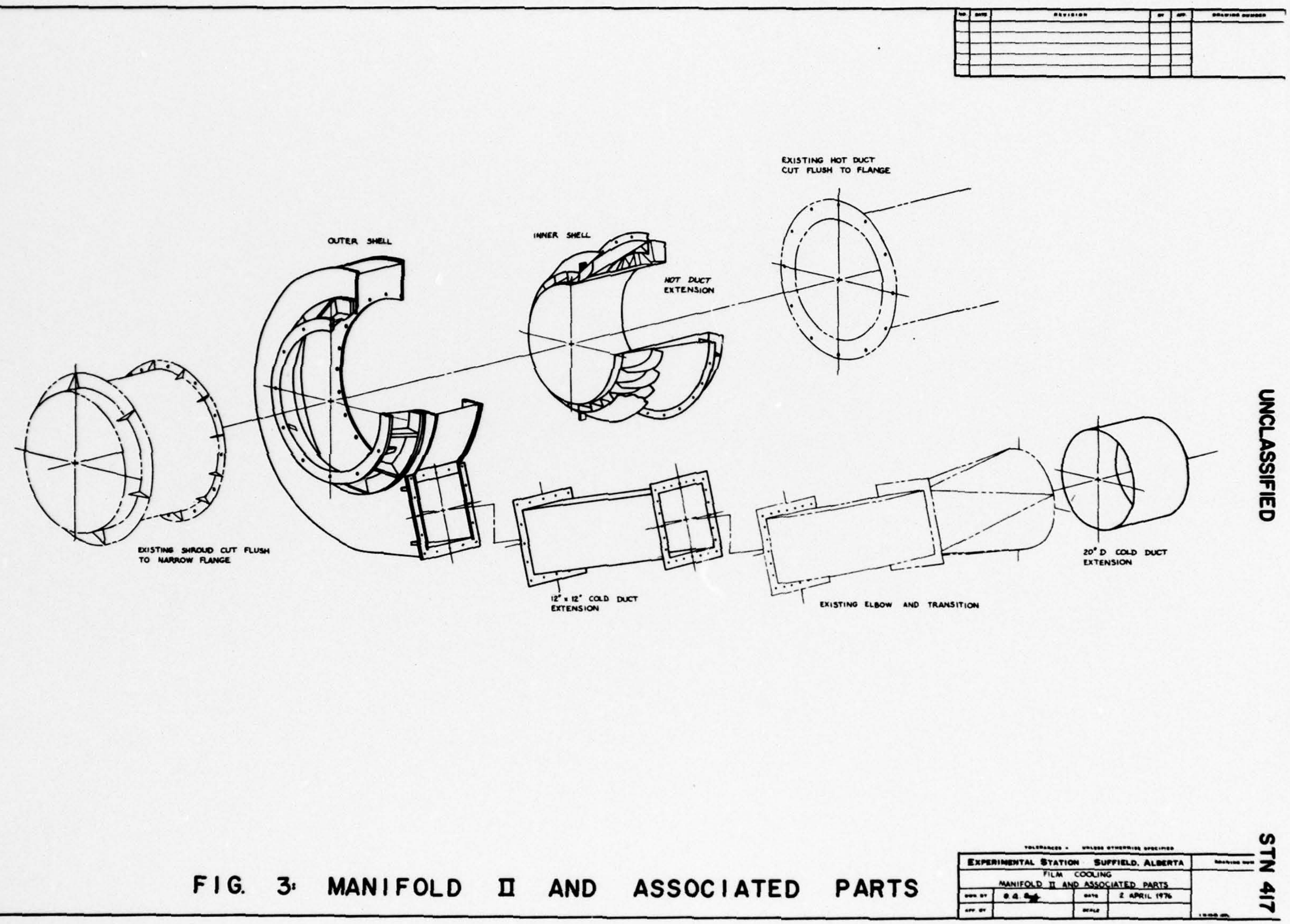

FIG. 3: MANIFOLD II AND ASSOCIATED PARTS

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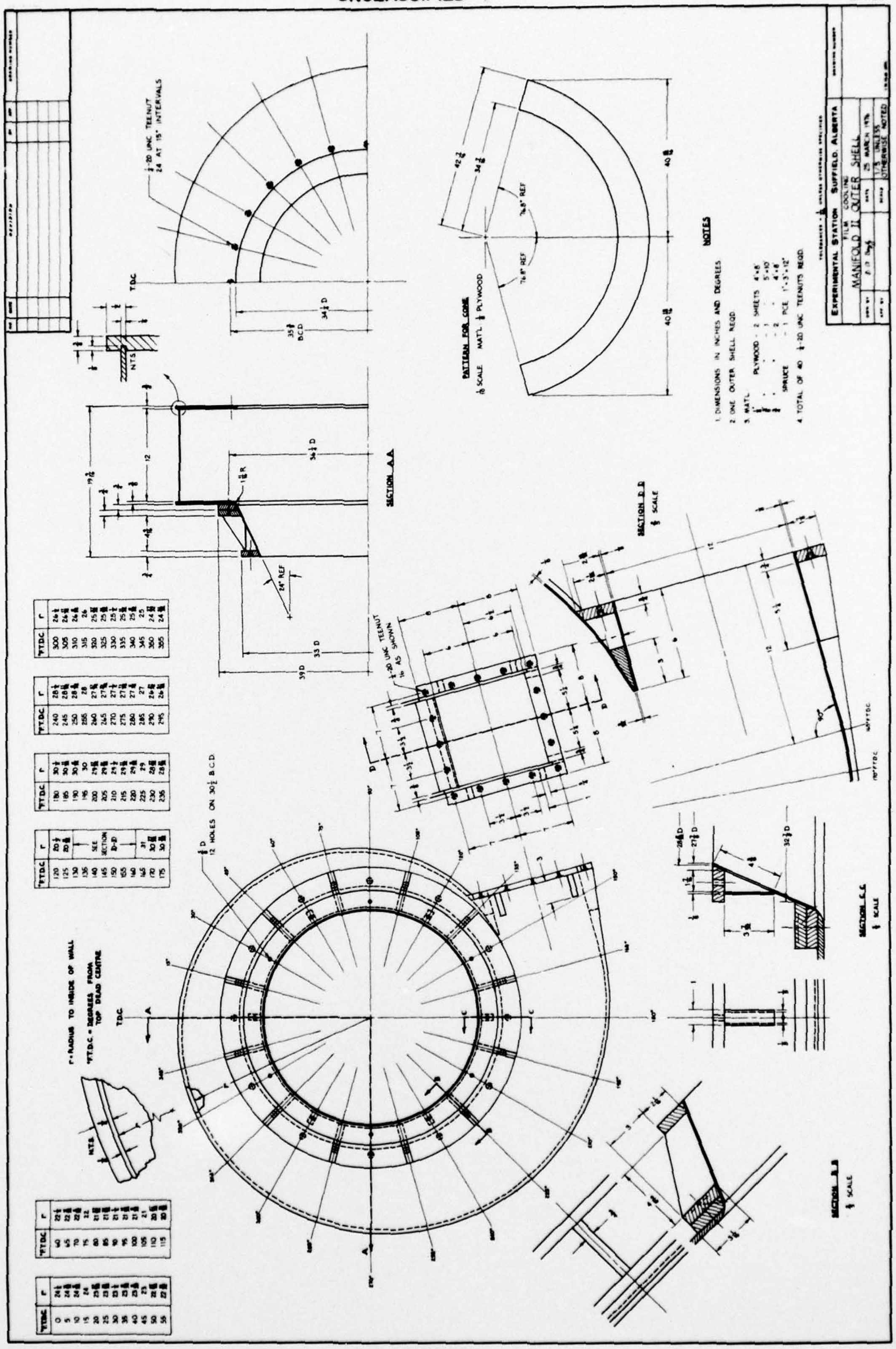


FIG. 4: MANIFOLD II OUTER SHELL

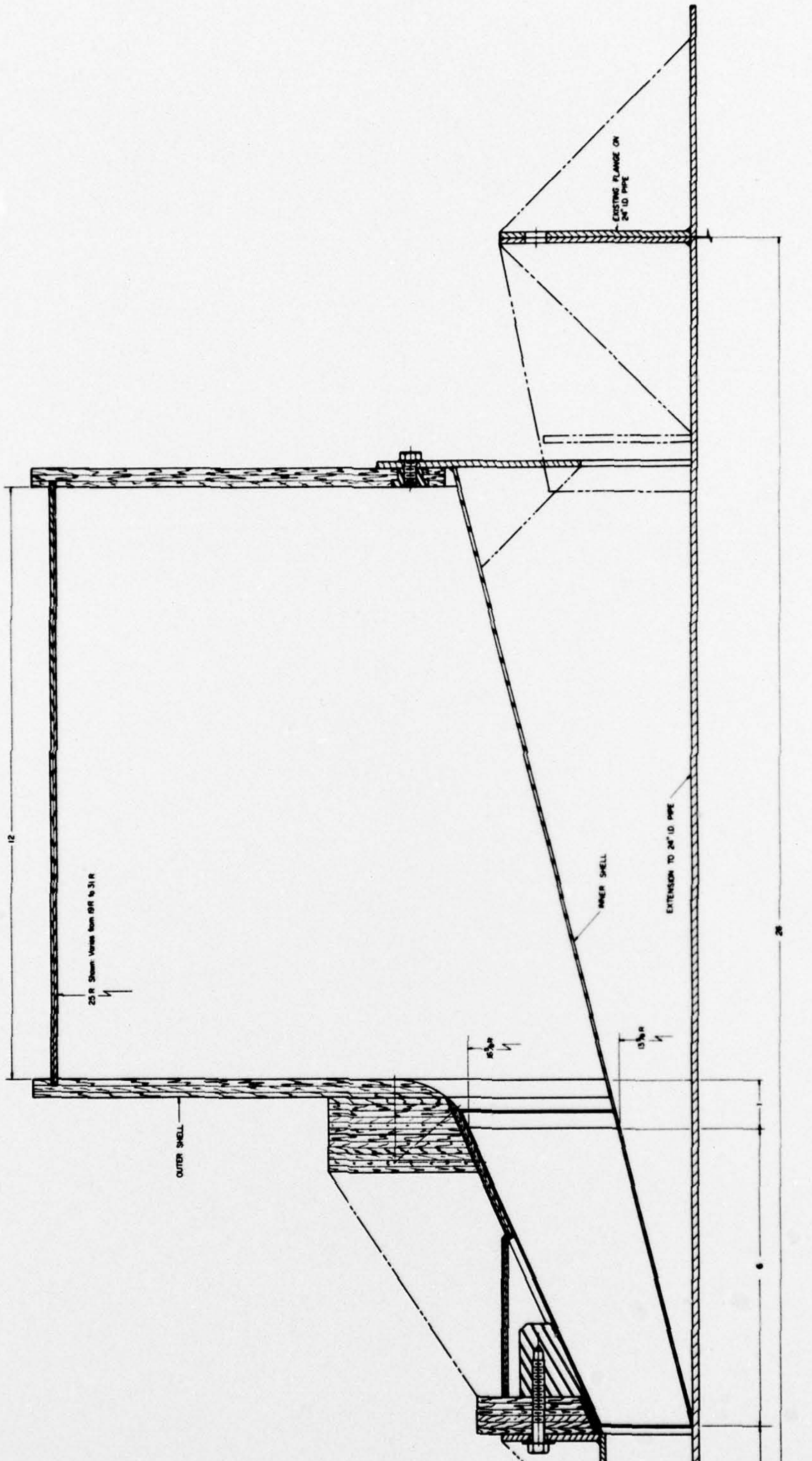


FIG. 5: SECTION THROUGH MANIFOLD II

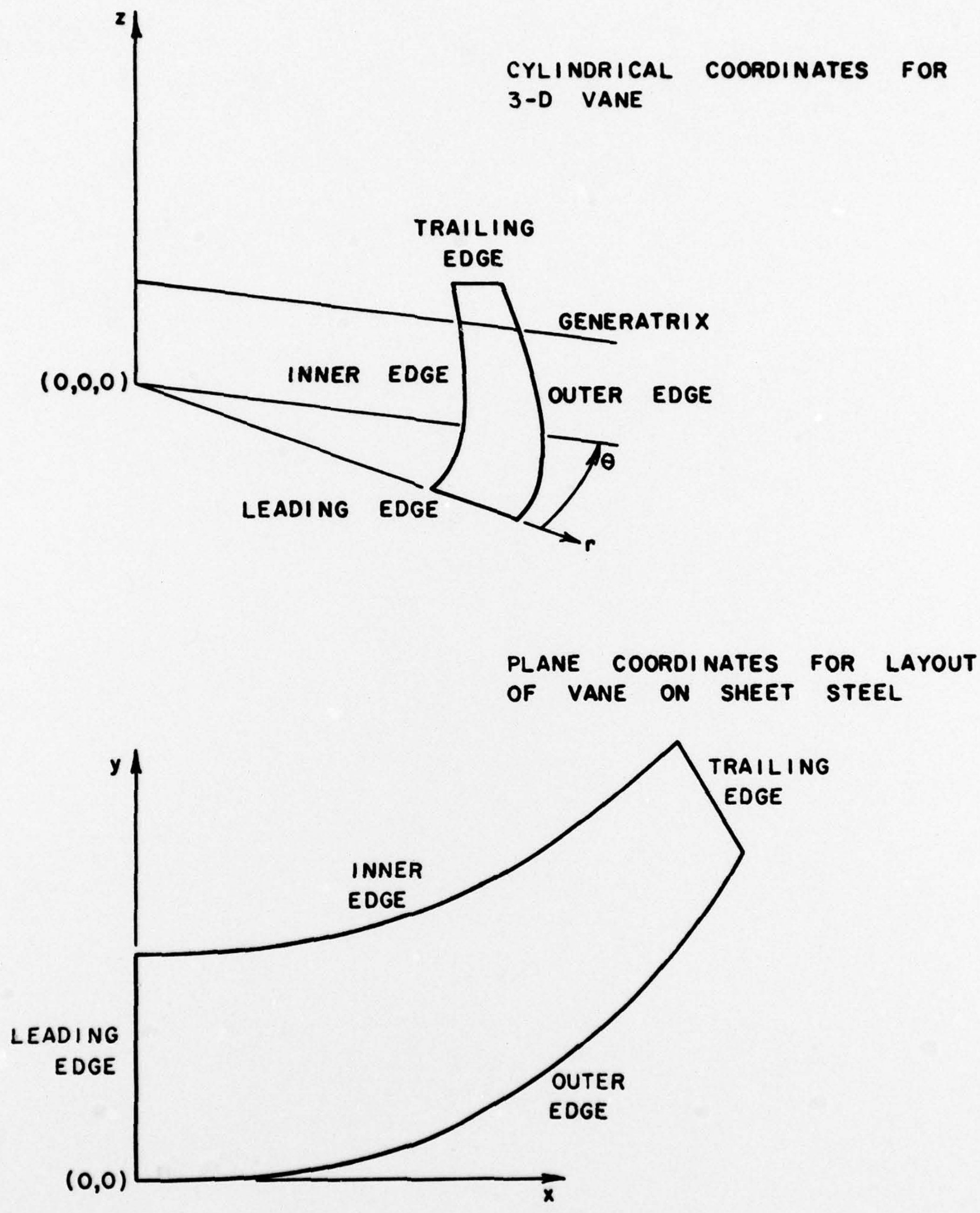


FIG. 6: COORDINATE DEFINITIONS

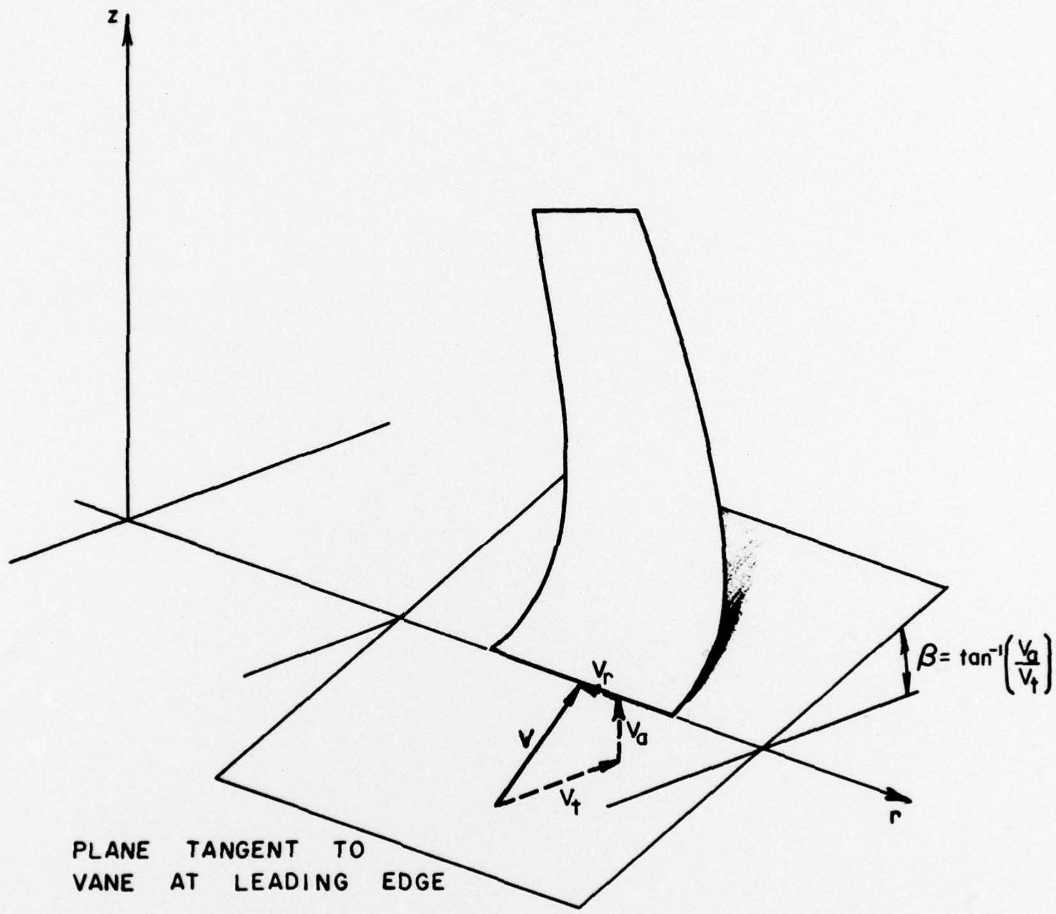


FIG. 7: LEADING EDGE TANGENT PLANE ANGLE

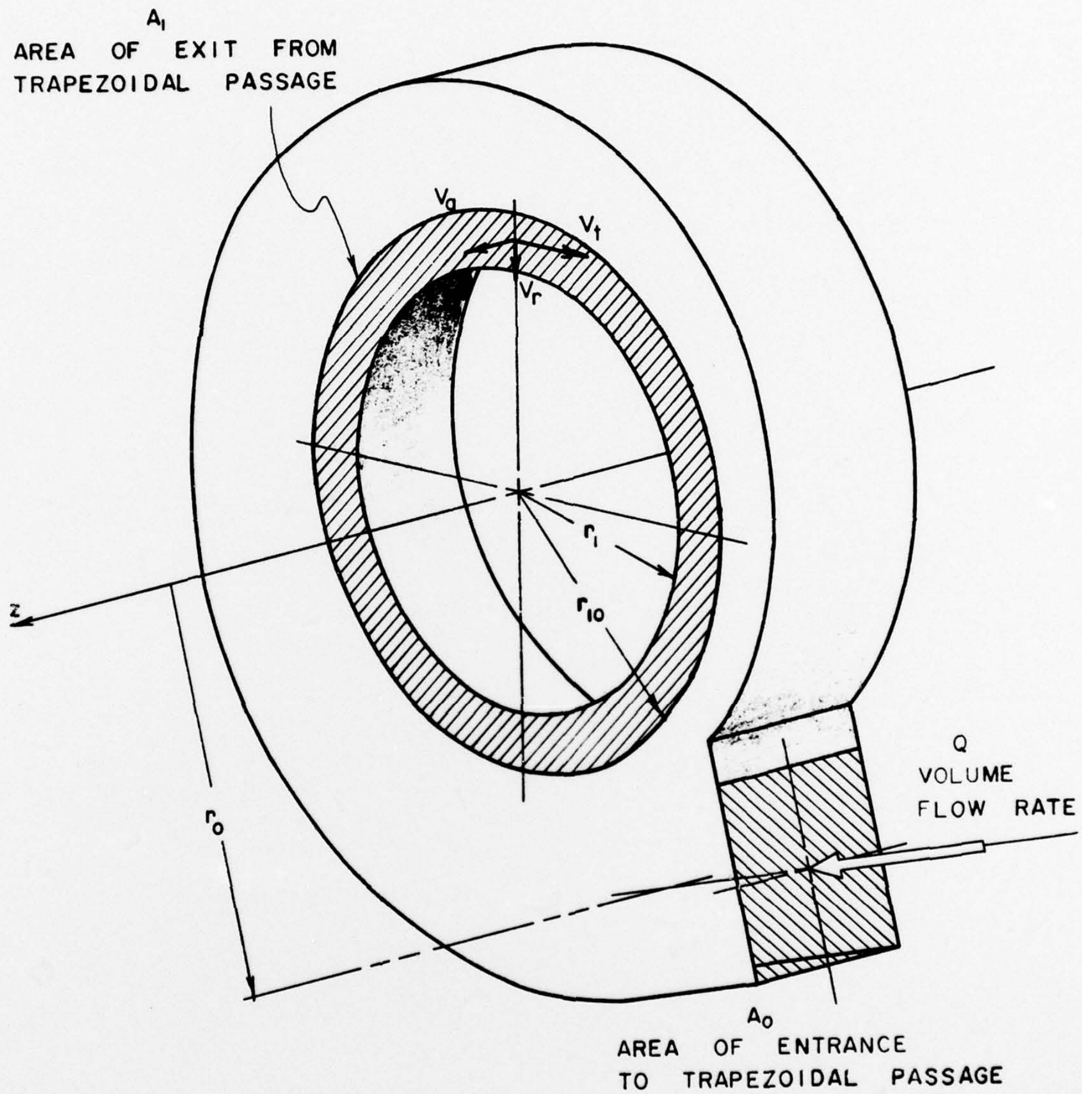
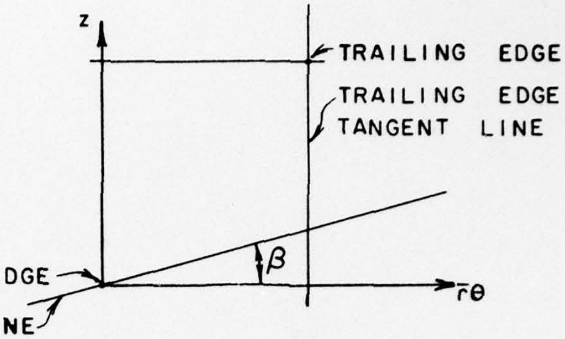


FIG. 8: CALCULATION OF V_a AND V_t

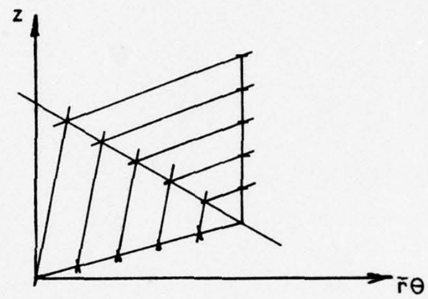
(1)

DRAW LEADING AND TRAILING EDGE TANGENT LINES.



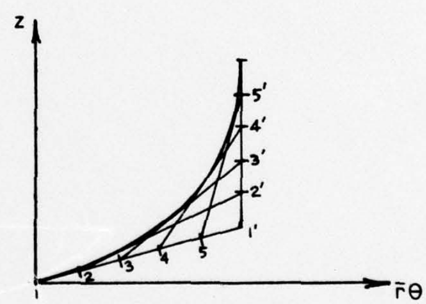
(2)

DIVIDE EACH LINE INTO THE SAME NUMBER OF EQUAL SEGMENTS.



(3)

JOIN POINTS 2,2' 3,3' ETC. DRAW TANGENT CURVE.



(4)

MEASURE Z AT REGULAR INTERVALS OF θ.

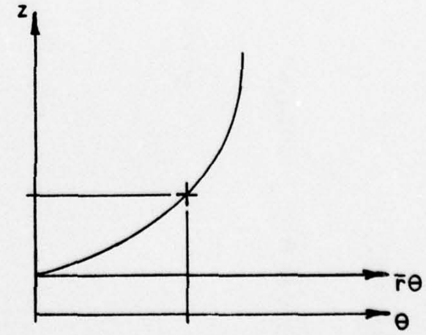


FIG. 9: z VERSUS $\bar{r}\theta$

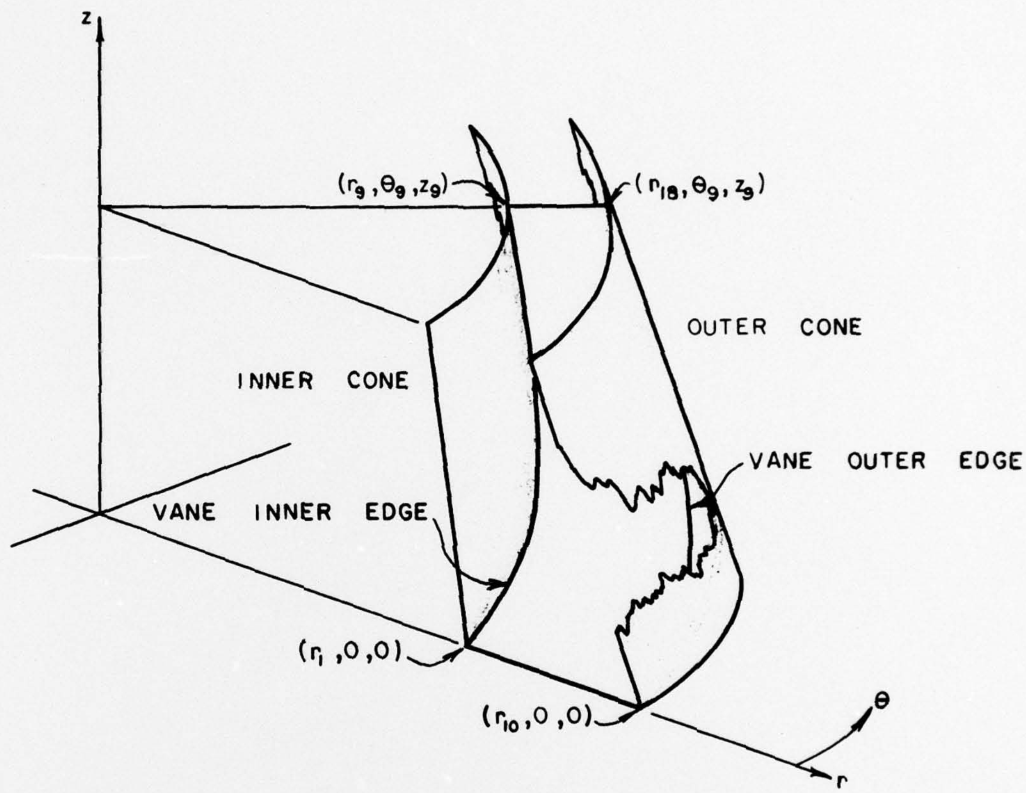


FIG. 10: INNER AND OUTER EDGES OF VANE

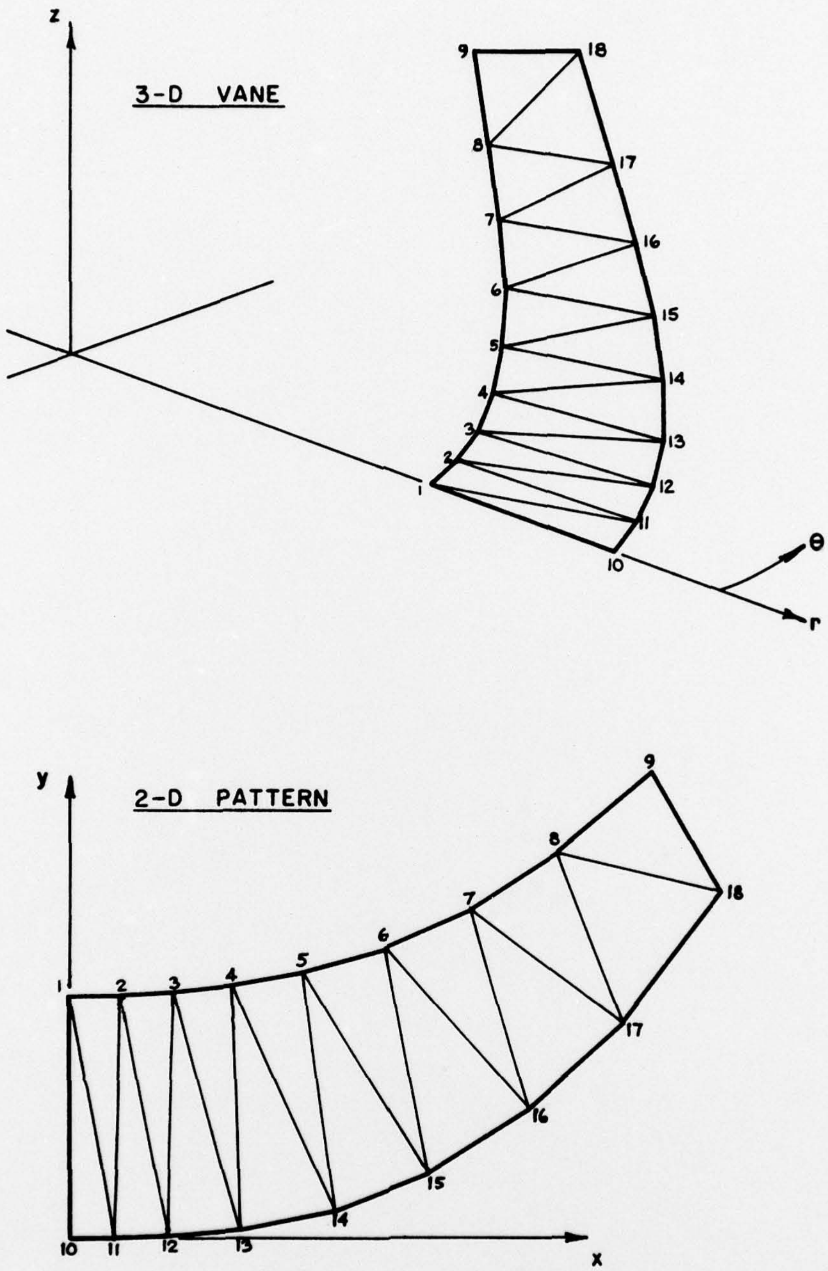


FIG. 11: VANE COMPOSED OF TRIANGULAR ELEMENTS

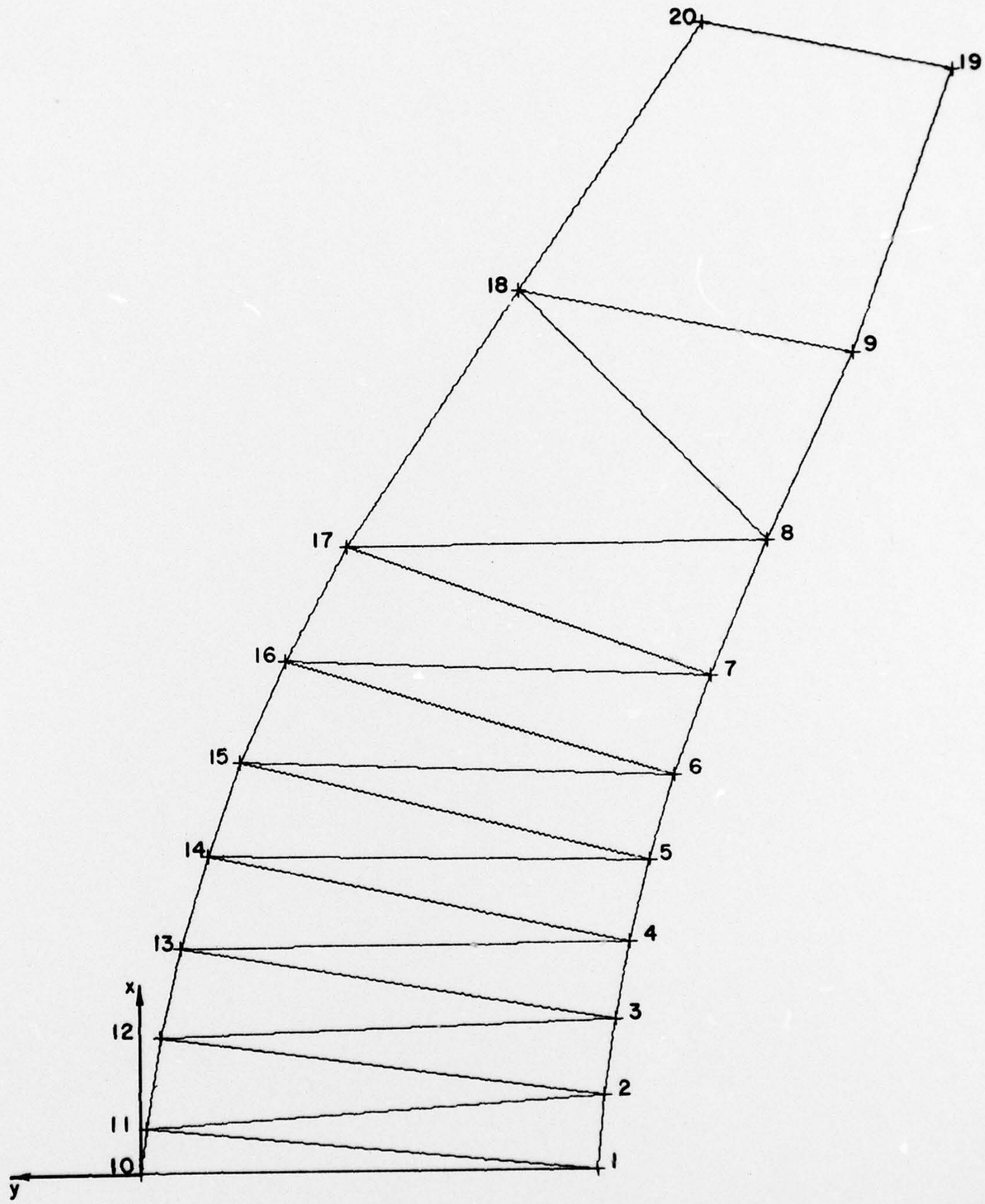


FIG. 12: FULL SCALE VANE PATTERN

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13. ABSTRACT

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