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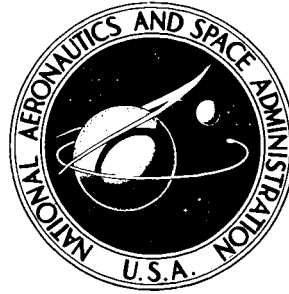
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OPTIMUM RUNWAY ORIENTATION
RELATIVE TO CROSSWINDS

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16. ABSTRACT

Specific magnitudes of crosswinds may exist that could be constraints to the success of an aircraft mission such as the landing of the proposed space shuttle. A method is required to determine the orientation or azimuth of the proposed runway which will minimize the probability of certain critical crosswinds. Two procedures for obtaining the optimum runway orientation relative to minimizing a specified crosswind speed are described and illustrated with examples. The empirical procedure requires only hand calculations on an ordinary wind rose. The theoretical method utilizes wind statistics computed after the bivariate normal elliptical distribution is applied to a data sample of component winds. This method requires only the assumption that the wind components are bivariate normally distributed. This assumption seems to be reasonable. Studies are currently in progress for testing wind components for bivariate normality for various stations. The close agreement between the theoretical and empirical results for the example chosen substantiates the bivariate normal assumption.

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INTRODUCTION

Runway orientation is undoubtedly influenced by a number of factors —
perhaps winds, terrain features, population interference, etc. In some
cases, the frequency of occurrence of crosswind components of some signi-
ficant speed may have received insufficient consideration. If, for example,
a runway for the space shuttle vehicles is being planned, it may be prudent
to consider the optimum runway orientation to minimize crosswind com-
ponents of, for example, 20 knots. Aligning the runway with the prevailing
wind will not ensure that crosswinds of this magnitude will be minimized.
In fact, two common synoptic situations (one producing light easterly winds,
and the other causing strong northerly winds) might exist in such a relation-
ship that a runway oriented with the prevailing wind might be the least use-
ful to an aircraft constrained by crosswind components $\geq$ 20 knots. Two
methods (one empirical, the other theoretical) of determining the optimum
runway orientation to minimize critical crosswind component speeds are
described below. Both methods gave identical results for the Cape Kennedy,
Florida, winds shown in Table 1.

EMPIRICAL METHOD

The following paragraphs outline a short procedure (one requiring
only a desk calculator and a wind rose) for determining the best runway
orientation relative to some specified crosswind component.

From the ordinary wind rose (Table 1), the percentage frequency
of a number of wind speeds and directions can be obtained. For this pro-
cedure, the percentage frequency or number of cases in each class interval
or "box" is assumed to be located at the class mark.

It is apparent that, if two of the reported wind directions (opposites)
are chosen as a runway orientation, the crosswind component contributed by
each box can be obtained from the product of the wind speed and the sine

TABLE 1. ANNUAL WIND ROSE AND STATISTICAL SUMMARY FOR CAPE KENNEDY.

Speed Direction	Knots							Total All Obs.		Speed (Knots)	
	1-9	10-19	20-29	30-39	40-49	50-59	60-74	Obs.	%	Sum	Mean
N	1 605	2 825	1339	73	3			5 845	7.0	83 239	14.2
NNE	1 318	2 323	446	44	2			4 133	4.9	51 145	12.4
NE	1 271	2 180	351	49	11			3 862	4.6	47 456	12.3
ENE	1 708	3 109	603	54	9			5 483	6.5	68 326	12.5
E	2 342	4 264	601	50	5		1	7 263	8.7	88 086	12.1
ESE	2 882	4 879	598	29	11	2		8 401	10.0	99 428	11.8
SE	2 637	3 841	691	16	4	2	1	7 212	8.6	85 520	11.9
SSE	2 203	3 165	625	23	3	1	3	6 023	7.2	71 873	11.9
S	2 318	2 549	436	21	6	2		5 332	6.4	59 099	11.1
SSW	2 197	1 605	364	59	9	1		4 235	5.1	45 454	10.7
SW	1 777	1 548	288	39	5	3	1	3 661	4.4	39 733	10.9
WSW	1 456	1 253	222	34	5	5		2 975	3.6	32 476	10.9
W	1 553	1 389	402	66	9			3 419	4.1	40 518	11.9
WNW	1 510	1 527	514	50	2			3 603	4.3	43 621	12.1
NW	2 428	2 866	688	62	4			6 048	7.2	72 363	12.0
NNW	1 949	2 216	1111	101	3			5 380	6.4	71 943	13.4
Calm								854	1.0		
Totals	31 174	41 539	9279	770	91	16	6	83 729		1 000 280	11.9
Percent	37.2	49.6	11.1	0.9	0.1	0.0	0.0		100.0		
Mean Speed (Knots) By Group	6.1	13.8	22.6	32.6	42.5	52.4	63.5				

TABLE 1. (Concluded)

θ 83	S_v 13.359	V_r 1.787	$\Sigma x_1 x_2$ −1 048 423.600	ΣV^2 15 210 144.000	$nS_{x_2}/\Sigma x_1$ −5.441	S_v/V_r 7.47	σ_a 10.136	σ_b 8.702	σ_s 6.309
n 83 729	S_{x_1} 9.230	$\bar{x}_1$ −1.775	Sum of E Components (Σx_1) −148 628.750	Σx_1^2 7 396 563.000	$nS_{x_1}/\Sigma x_1$ −5.200	S_v/σ_s 2.12	$r_{x_1 x_2}$ −0.145	e 1.165	
ψ 126	S_{x_2} 9.658	$\bar{x}_2$ −0.210	Sum of N Components (Σx_2) −17 563.027	Σx_2^2 7 813 581.000	$nS_{x_2}/\Sigma x_2$ −46.043	$V_r/\bar{v}$ 0.15	ΣV 1 000 280	$\bar{v}$ 11.9	

Notes:

S_{x_1} = Standard deviation of east components.

S_{x_2} = Standard deviation of north components.

S_v = Standard vector deviation of wind velocity.

$r_{x_1 x_2}$ = Correlation coefficient of north and east components.

$\bar{v}$ = Average wind speed.

V = Scalar wind speed.

σ_a = Standard deviation of wind components along the major axis of the distribution.

σ_b = Standard deviation of wind components perpendicular to the major axis of the distribution.

ψ = Angle of rotation of the major axis of the wind distribution counterclockwise from EW direction.

θ = Resultant wind direction.

V_r = Resultant wind speed.

σ_s = Standard deviation of wind speeds.

e = σ_a/σ_b.

of the angle between the wind direction and the runway orientation. Since wind directions are usually given to 16 points, the angles between the wind direction and the runway will be 22.5, 45, 67.5, and 90 deg. For example, if the runway orientation is chosen as EW, then all ENE, ESE, WNW, and WSW winds will be 22.5 deg off the runway. Likewise, NE, SE, NW, and SW will be 45 deg off, NNE, SSE, NNW, and SSW will be 67.5 deg off, and N and S will be 90 deg off. From Figure 1 it is apparent that each wind direction and wind speed will make a contribution to the total percent frequency of cross-wind components. Since several wind directions in the same wind speed category
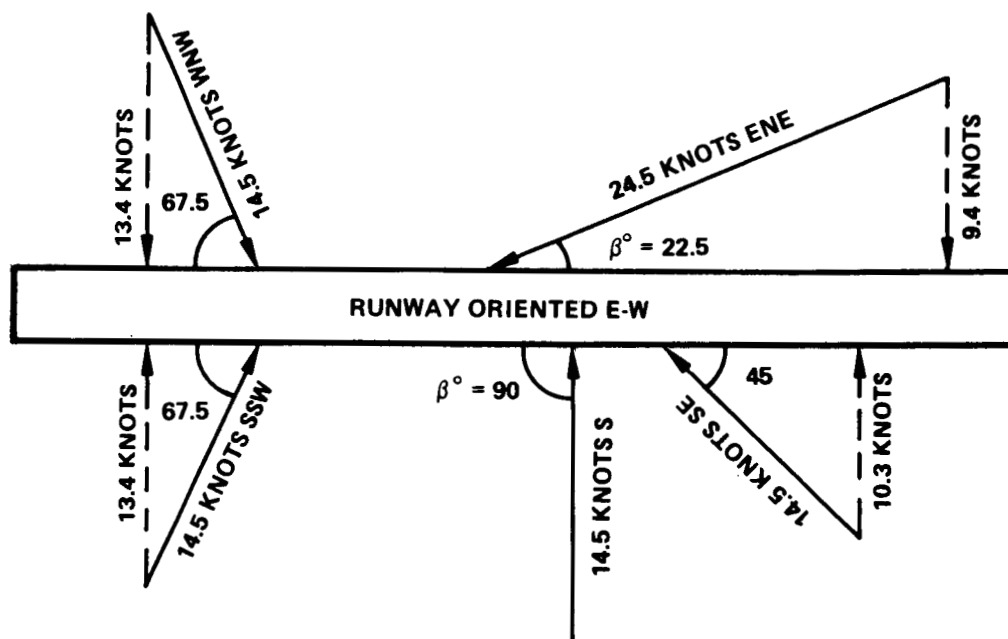

Figure 1. Runway crosswind component calculation.

will produce the same crosswind component, these boxes should be summed. For example, under the 10-19 category, sum NE, SE, NW, and SW (2180 + 3841 + 2866 + 1548 = 10 435) to obtain the frequency of crosswind components of 10.3 knots (14.5 sin 45 deg = 10.3). This process should be continued until all boxes except E-W have been used to compute a crosswind component.

In summary, the crosswind component computation procedure consists of the following steps:

1. Compute all possible crosswind components — the product of each wind speed and the sine of 22.5, 45, 67.5, and 90 deg.

2. Sum all boxes that contribute the same crosswind component for a specified runway orientation. Compute the frequency and percent frequency for each crosswind speed.

3. Order the crosswind component speeds from the largest to the smallest and tabulate the percent frequency of occurrence opposite each crosswind component.

4. Form the cumulative percentage frequency (CPF) from the values tabulated in step 3., starting with the highest wind speed. This CPF gives a description of the crosswind components for a single runway.

5. Interpolate the CPF for the desired wind speed. This interpolated value gives the probability in percent of equaling or exceeding the specified crosswind component for that runway orientation. From the few cases examined, it appears that the interpolation should be made assuming a normal distribution.

Of course, the procedure must be repeated for each pair of opposite wind directions (runway orientations) to determine the optimum runway orientation relative to a critical crosswind component.

This procedure was applied to the Cape Kennedy annual wind rose shown in Table 1, except that hurricane associated winds $\geq$ 50 knots were removed on the premise that landing operations would not be conducted during such periods. (Table 1 was prepared from hourly peak wind measurements made from September 1958 through June 1969.) Results of the analysis (Fig. 2), for which 20 knots was selected as the critical crosswind speed, indicate that the best runway orientation relative to speeds of this magnitude is about 150 to 330 deg true.
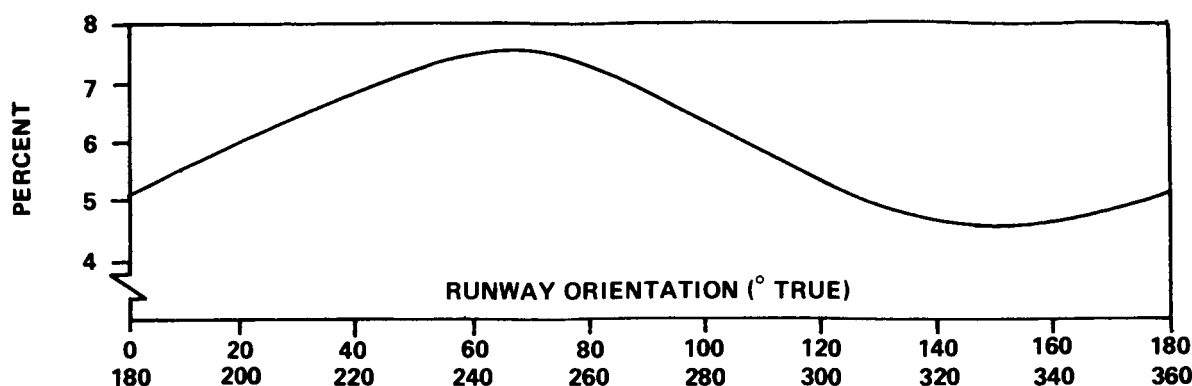
Figure 2. Cape Kennedy percentage frequency of exceedance of peak crosswind components $\geq$ 20 knots versus runway orientation.

THEORETICAL METHOD

For Cape Kennedy, the assumption has been made that wind components are bivariate normally distributed; i.e., a vector wind data sample is resolved into wind components in a rectangular coordinate system and the bivariate normal elliptical distribution is applied to the data sample of component winds. For example, let x_1 and x_2 be normally distributed variables (the wind components at Cape Kennedy) with parameters (ξ_1, σ_1) and (ξ_2, σ_2). ξ_1 and ξ_2 are the respective means, while σ_1 and σ_2 are the respective standard deviations. Let ρ be the correlation coefficient, which is a measure of the dependence between x_1 and x_2. Now, the equation of the bivariate normal density function is

$$p(x_1, x_2) = \left[2\pi\sigma_1\,\sigma_2\,(1 - \rho^2)^{1/2} \right]^{-1} \exp\left\{ -[2(1 - \rho^2)]^{-1} \left[\left(\frac{x_1 - \xi_1}{\sigma_1} \right)^2 \right. \right.$$

$$\left. \left. - 2\rho \left(\frac{x_1 - \xi_1}{\sigma_1} \right) \left(\frac{x_2 - \xi_2}{\sigma_2} \right) + \left(\frac{x_2 - \xi_2}{\sigma_2} \right)^2 \right] \right\} \quad . \quad (1)$$

Let α be any arbitrary angle in the rectangular coordinate system and let the sample estimates of ξ_1, ξ_2, σ_1, σ_2, and ρ be denoted by $\overline{X}_1$, $\overline{X}_2$, S_{x_1}, S_{x_2}, and $r_{x_1 x_2}$, respectively. From the statistics in the (x_1, x_2) space, the statistics for any rotation of the axes of the bivariate normal distribution through any arbitrary angle α may be computed as given below [1].

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Let (y_1, y_2) be the new space after rotation with orthogonal axes y_1 and y_2. Let $\bar{Y}_1$, $\bar{Y}_2$, S_{y_1}, S_{y_2}, and $r_{y_1 y_2}$ be the means, standard deviations, and correlation coefficient in the (y_1, y_2) space. From Reference 1,

$$\bar{Y}_1 = \bar{X}_1 \cos \alpha + \bar{X}_2 \sin \alpha$$

$$\bar{Y}_2 = \bar{X}_2 \cos \alpha - \bar{X}_1 \sin \alpha$$

$$S_{y_1} = \left(S_{x_1}^2 \cos^2\alpha + S_{x_2}^2 \sin^2\alpha + 2S_{x_1 x_2} \cos \alpha \, \sin \alpha \right)^{1/2}$$

$$S_{y_2} = \left(S_{x_2}^2 \cos^2\alpha + S_{x_1}^2 \sin^2\alpha - 2S_{x_1 x_2} \cos \alpha \, \sin \alpha \right)^{1/2} \quad .$$

$$r_{y_1 y_2} = \frac{S_{y_1 y_2}}{S_{y_1} S_{y_2}} \quad ,$$

(2)

where $S_{x_1}^2$, $S_{x_2}^2$, and $S_{x_1 x_2}$ are the variances and covariance in the (x_1, x_2) space and $S_{y_1 y_2}$ is the covariance in the (y_1, y_2) space.

In equations (2), all statistics on the right side are available for Cape Kennedy or may be computed from existing data (Table 1).

Equations (2) give the statistics in the (y_1, y_2) space (this is the space after rotation through any angle α) that defines the bivariate probability density function (1).

The existing wind statistics for Cape Kennedy (Table 1) are for the reference angle $\alpha = 90$ deg; i.e., the (x_1, x_2) space is for $\alpha = 90$ deg.

Let $\Delta\alpha$ denote the desired increments for which runway orientation accuracy is required; e.g., one may wish to minimize the probability of cross-winds with a runway orientation accuracy down to $\Delta\alpha = 10$ deg. This means we must rotate the bivariate normal axes through every 10 deg beginning at $\alpha = 90$ deg [the (x_1, x_2) space]. It is only necessary to rotate the bivariate normal surface through 180 deg, since the distribution is symmetric in the

other two quadrants. This process will result in 18 sets of statistics in the (y_1, y_2) space obtained from equations (2). y_1 is the head wind component while y_2 is the crosswind component. Since we are concerned with minimizing the probability of crosswinds (y_2) only, we now examine the marginal distributions $p(y_2)$ for the 18 orientations (α). Since $p(y_1, y_2)$ is bivariate normal, 18 marginal distributions $p(y_2)$ must be univariate normal:

$$p(y_2) = \left[\sigma_2 (2\pi)^{1/2} \right]^{-1} \exp \left\{ -\tfrac{1}{2} \left[(y_2 - \xi_2)/\sigma_2 \right]^2 \right\} . \tag{3}$$

ξ_2 and σ_2 are replaced by their sample estimates $\bar{Y}_2$ and S_{y_2}. Now, let

$$z = \frac{Y_2 - \bar{Y}_2}{S_{y_2}} , \tag{4}$$

where y_2 is the critical crosswind of interest. z is a standard normal variable and the probability of its exceedance is easily calculated from tables of the standard normal integral. Since a right or left crosswind (y_2) is a constraint to an aircraft, the critical region (exceedance region) for the normal distribution is two-tailed; i.e., we are interested in twice the probability of exceeding $|y_2|$. Let this probablity of exceedance or risk = R.

A computer program is available for computing the statistics in the (y_1, y_2) space defined by equations (2), the integral of equation (3), and the risk R (see Appendix A). The Cape Kennedy data given in Table 1 are used as an example. The input to the program is $\bar{X}_1 = -1.775$, $\bar{X}_2 = -0.210$, $S_{x_1} = 9.230$, $S_{x_2} = 9.658$, $r_{x_1 x_2} = -0.145$, and $\Delta\alpha = 10$ deg. Let the critical crosswind component $x_2 = 20$ knots as in the empirical example in the preceding section. To obtain a valid comparison to the empirical probability, we will compute R = the probability of exceeding or equalling $x_2 = 20$ knots. Table 2 summarizes the runway orientation angles α, the standard normal variate z, and the risk R for Cape Kennedy.

For this example, the risk R = 5.63 percent of exceeding or equalling a 20-knot crosswind is a minimum occurring at the runway orientation $\alpha = 150 - 330$ deg. This theoretical result verifies the empirical conclusion arrived at in the previous section.

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TABLE 2. SUMMARY OF RUNWAY ORIENTATION (α) VERSUS
RISK (R), CAPE KENNEDY.

α (deg)	z	R (%)	α (deg)	z	R (%)
90	1.57	11.53	180	1.82	6.91
100	1.65	9.93	190	1.76	7.79
110	1.72	8.47	200	1.71	8.77
120	1.80	7.25	210	1.66	9.76
130	1.86	6.36	220	1.61	10.69
140	1.89	5.82	230	1.58	11.48
150	1.91	5.63	240	1.55	12.07
160	1.90	5.78	250	1.54	12.45
170	1.86	6.22	260	1.53	12.61

The method described to determine the orientation of a runway which will minimize the probability of critical crosswinds is accurate and expedient. The procedure described may be used for any station. Only parameters estimated from the data are required as input. Consequently, many runways and locations may be examined rapidly.

CONCLUSIONS

Either the empirical or theoretical method described in this report may be used to determine an aircraft runway orientation that minimizes the probability of critical crosswinds. Again, it is emphasized that the wind components must be bivariate normally distributed to use the theoretical method. The Cape Kennedy wind component raw data were not available for the example used in this report. The bivariate normal assumption may or may not be a good assumption. However, the Cape Kennedy sample illustrates

the method. The agreement between the theoretical and empirical methods is very good. As shown by Figure 2 and Table 2, the minimum and maximum probabilities occur at the same azimuths for both methods. The minimum risk of 5.63 percent for the theoretical method occurs at 150 deg. The minimum risk for the empirical approach also occurs at 150 deg as shown by Figure 2. The empirical risk is approximately 4.7 percent. The maximum risks for the two methods also occur at approximately the same orientation. The maximum theoretical risk of 12.61 percent occurs at 260 deg, while the maximum empirical risk of about 7.6 percent occurs at 250 deg. One may view the differences in the theoretical and empirical probabilities as a measure of the departure of the data from normality.

In practical applications, the following steps are suggested:

1. Test the component wind samples for bivariate normality if these samples are available. See Reference 2 for bivariate normal goodness-of-fit tests.[1]

2. If the component winds are available and cannot be rejected as bivariate normal using the bivariate normal goodness-of-fit test, use the theoretical method since it is more expedient and easily programmed.

3. If the component wind data samples are not available and there is doubt concerning the assumption of bivariate normality of the wind components, use the empirical method.

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APPENDIX. COMPUTER PROGRAM FOR OPTIMUM RUNWAY ORIENTATION RELATIVE TO CROSSWINDS

Legend

α — Runway orientation

$\alpha(R)$ — Orientation or angle at which the wind component statistics are computed from the data sample

$\bar{X}_1$ — Mean of the head-tail winds at orientation $\alpha(R)$

$\bar{X}_2$ — Mean of the crosswinds at orientation $\alpha(R)$

S_{x_1} — Standard deviation of head-tail winds at $\alpha(R)$

S_{x_2} — Standard deviation of crosswinds at $\alpha(R)$

$S_{x_1 x_2}$ — Covariance at $\alpha(R)$

$R_{x_1 x_2}$ — Correlation coefficient at $\alpha(R)$

$\bar{Y}_1$ — Mean of the head-tail winds at orientation α

$\bar{Y}_2$ — Mean of the crosswinds at orientation α

$S^2_{y_1}$ — Variance of the head-tail winds at α

S_{y_1} — Standard deviation of the head-tail winds at α

$S^2_{y_2}$ — Variance of the crosswinds at α

S_{y_2} — Standard deviation of the crosswinds at α

$S_{y_1 y_2}$ — Covariance at orientation α

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$R_{y_1 y_2}$ Correlation coefficient at α

y_2 Critical crosswind

z   Standard normal variable

$F(y_2)$ Normal distribution function

R   Risk of exceeding $|y_2|$

INPUT

SALP   Starting α

ALPR αR

XB1 $\bar{X}_1$

XB2 $\bar{X}_2$

SX1 S_{x_1}

SX2 S_{x_2}

RX1X2 $R_{x_1 x_2}$

DALP $\Delta \alpha$

EALP   End or Maximum α

NV   No. of Y2

Y2   Table of Y2

      The first Y2 is taken and the program is utilized with the starting α. α is then increased by DALP and the program is utilized again. This is

repeated until EALP (maximum α) is reached. The next Y2 is taken and the process is repeated. This is continued until all of the Y2's have been used. A transfer is then made to STATEMENT to see if more data are to be read in. If not, the program terminates. Usually $\dot{Y}2$ is the only data that vary.

Note: The STATEMENT following STATEMENT 10 is an end-of-file check. If there are no more data the program terminates. This end-of-file test may not be compatible with other computers.

```
DIMENSION Y2(100)
NR=5
NW=6
D1=.49867347E-01
D2=.71191006IF-01
D3=.32775263E-02
D4=.3800365F-04
D5=.4889066E-04
DF=.5383E-05
WRITE(NW,10)
10 FORMAT(1H1,53X,26HRUNWAY ORIENTATION PROGRAM//)
READ(NR,3,ERR=35,END=35)SALP,ALPR,XB1,XB2,SX1,SX2,RX1X2,DALP,EALP
3 FORMAT(8F10.0)
READ(NR,11)NV
11 FORMAT(I10)
READ(NR,12)(Y2(I),I=1,NV)
12 FORMAT(8F10.0)
DO 13 K=1,NV
ALP=SALP
7 AH=ALPR-ALP
AL=AH+.01745329
FR=COS(AL)
ER1=SIN(AL)
ER2=SX2**2
ER3=SX1**2
YB1=XB1+FR+XB2*ER1
YB2=-XB1*EP1+XB2*FR
FR4=ER**2
FR5=ER1**2
SX1X2=RX1X2*SX1*SX2
SY1Y2=SX1X2*(ER4-ER5)+ER*ER*(ER2-ER3)
TRM=2.0*SX1X2*FR4*ER1
SY12=ER2*EP4*ER2*ER5+TRM
SY1=SQRT(SY12)
IF(SY1)80,31,80
80 SY22=ER2*ER4+ER3*ER5-TRM
SY2=SQRT(SY22)
IF(SY2)34,31,34
31 IF(SY1Y2)87,39,88
87 RY1Y2=-1.0
```

```
00204   41*          GO TO 39
00205   42*   88     RY1Y2=1.0
00206   43*          GO TO 39
00207   44*   89     RY1Y2=0.0
00210   45*          GO TO 39
00211   46*   34     RY1Y2=SY1Y2/(SY1*SY2)
00212   47*   39     Z=(Y2(K)-Y321/SY2
00213   48*          IF(Z)14,15,15
00216   49*   15     IZ=Z
00217   50*          GO TO 16
00220   51*   14     IZ=-1.0*Z
00221   52*   16     IZ2=IZ*IZ
00222   53*          IZ3=IZ2*IZ
00223   54*          IZ4=IZ2*IZ2
00224   55*          IZ5=IZ4*IZ
00225   56*          IZ6=IZ5*IZ2
00226   57*          ER=(1.0+D1*IZ2+D2*IZ2+D3*IZ3+D4*IZ4+D5*IZ5+D6*IZ6)**(-16)
00227   58*          IFY2=1.0-.5*ER
00230   59*          IF(Z)17,18,18
00233   60*   18     FY2=IFY2
00234   61*          GO TO 19
00235   62*   17     FY2=1.0-IFY2
00236   63*   19     R=2.0*(1.0-FY2)
00237   64*          WRITE(NW,6)ALP,ALPR,XR1,XR2,SX1,SX2,SX1X2,RX1X2,R
00265   65*    6     FORMAT(18X,5HALPHA=E13.8.5X,6HALPHAR1=E13.8.5X,6HXBAR1=E13.8.5X,
00255   67*         1HXR1,XR2=E13.8.5X,9HSX2   =E13.3.5X,
00255   68*         1HSX1X2=E13.8.5X,6HRX1X2=E13.8//19X,6HYBAR1=E13.8//19X,
00255   69*         19HYBAR2   =E13.8.5X,6HS2X1=E13.8.5X,5HSY1   =E13.8//19X,
00265   70*         1HSY2X2   =E13.8.5X,9HSY2
00255   71*         1HRY1Y2=E13.8//19X,6HY2=E13.8.5X,
00265   72*         1HFY2=E13.8.5X,9HFY2=E13.8.5X,9HZ
00266   73*          IF(EALP-ALP-.00)120,20,5
00271   74*          ALP=ALP+DELP
00272   75*          GO TO 7
00273   76*   20     WRITE(NW,10)
00275   77*   13     CONTINUE
00277   78*          GO TO 10
00300   79*   35     STOP
00301   80*          END
```

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