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TECHNICAL REPORT

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TABLES FACILITATING CONFIDENCED RELIABILITY CALCULATIONS FOR THE NORMAL OR LOGNORMAL DISTRIBUTION

BY

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TABLES FACILITATING CONFIDENCED RELIABILITY CALCULATIONS FOR THE NORMAL OR LOGNORMAL DISTRIBUTION

ABSTRACT

Small sample size tables are presented which facilitate reliability—mission life calculations at a given confidence level. The tables are calculated using the exact sampling distribution of the normal reliability estimator. A computer program is included which will enable one to calculate more extensive tables for different sample sizes and confidence levels.

Cross-Reference Data

Reliability
Confidence interval
Neyman
Estimator
Exact sampling distribution
Gaussian quadrature
Nonlinear equations

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1. INTRODUCTION

The specific purpose of this report is to enable one, through the use of tables, to calculate mission life of a component at a given confidence level for a given confidenced reliability.

It is assumed that a representative sample of failures is available; the sample size must be two or greater. The statistical theory underlying this report is available in ref. (1).

2. NOTATION

$\Gamma(x)$ = gamma function of x

$$= \int_0^\infty t^{x-1} e^{-t} dt$$

$\Phi(x)$ = standard normal distribution function of x

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{1}{2}t^2} dt$$

z_α = standard normal fractile function of α or the inverse of Φ. $\Phi(z_\alpha) = \alpha$

n = sample size

x = mission life

R_c = Confidenced Reliability (lower confidence bound on population reliability)

R* = Reliability point estimate

μ^*, σ^* = Maximum Likelihood estimates of normal parameters

$\mu_\ell^*, \sigma_\ell^*$ = Maximum Likelihood estimates of Lognormal parameters (sample mean and standard deviation of natural logs of data points).

C = confidence level

3. DESCRIPTION OF PROBLEM

The problem is:

given n, c and R_c, solve the following equation for z_{R^*}.

$$\frac{(1-c)\Gamma\left(\frac{n-1}{2}\right)}{2\left(\frac{n}{2}\right)^{\frac{n-1}{2}}} - \int_0^\infty s^{n-2} e^{-\frac{ns^2}{2}} \Phi\left[\sqrt{n}\left(z_{R_c} - s z_{R^*}\right)\right] ds = 0 \tag{1}$$

The point estimate of normal reliability is given by:

$$R^* = 1 - \Phi\left(\frac{x-\mu^*}{\sigma^*}\right) \tag{2}$$

$$\therefore \quad \frac{x-\mu^*}{\sigma^*} = z_{1-R^*} = -z_{R^*}$$

$$\therefore \quad x = \mu^* - \sigma^* z_{R^*} \tag{3}$$

Therefore, once Eqn. (1) is solved for z_{R^*}, the mission life x may easily be calculated for any μ^* and σ^*.

If one is restricted to a certain reliability R_c and a

certain confidence level C, the mission life calculation is solved once and for all by solving Eqn. (1) for a sufficiently large sequence of values of n.

The point estimate of lognormal reliability is given by:

$$R^* = 1 - \Phi\left(\frac{\ln x - \mu_\ell^*}{\sigma_\ell^*}\right) \tag{4}$$

$$\therefore \quad \frac{\ln x - \mu_\ell^*}{\sigma_\ell^*} = z_{1-R^*} = -z_{R^*}$$

$$\therefore \quad x = e^{\mu_\ell^* - \sigma_\ell^* z_{R^*}} \tag{5}$$

The same z_{R^*} that was calculated before from Eqn. (1) can be used to calculate mission life for the lognormal model also.

The method selected to solve Eqn. (1) is called the midpoint or bisection method. This method is probably the simplest and most straightforward method of solving nonlinear equations in one unknown. The method consists of:

1. Locating the root r between x_1 and x_2 (by observing a change of sign in the function).

2. Evaluating the function at the middle of the interval (x_1, x_2) and then observing on which side of the midpoint the function changes sign.

3. Redefining either x_1 or x_2 accordingly and returning to step 2 if the interval size is not sufficiently small.

The point at which this process is stopped is determined by the fact that an easily calculated upper bound on the relative error in the root is always available.

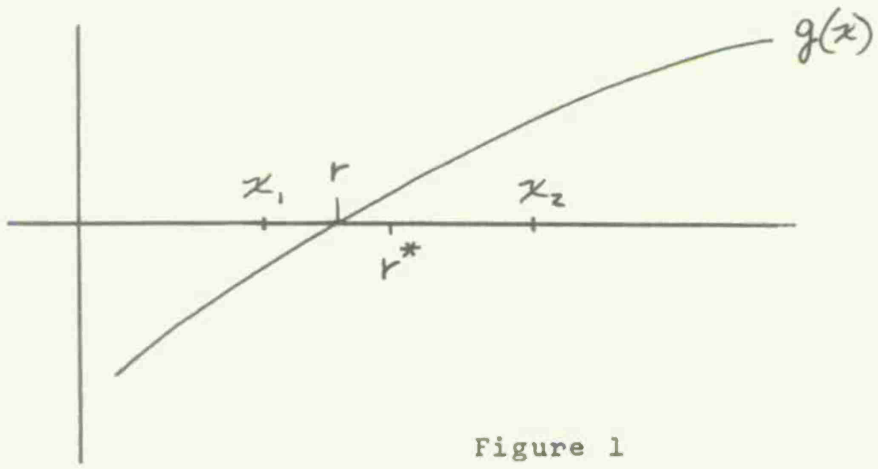


Figure 1

Referring to Fig. (1), suppose the process is to be stopped with the present values of x_1 and x_2. The final estimate of the true root r will be $r^* = (x_1 + x_2)/2$; therefore:

absolute error = $|r - r^*|$

relative error = $\rho = \left|\dfrac{r - r^*}{r}\right|$

$$\left|\frac{r-r^*}{r}\right| \leq \frac{\frac{1}{2}|x_2-x_1|}{|r|} \leq \frac{\frac{1}{2}|x_2-x_1|}{\min\{|x_1|,|x_2|\}}$$

$$= p^*$$

If the process is continued until p* is less than some desired fractional error, p will also be less than this error and the process may be halted. This is all true assuming that $g(x)$ can be evaluated accurately.

The next problem to be considered is evaluating the integrand in Eqn (1). Formulas 26.2.12 and 26.2.17 of ref. (2) are used to evaluate the normal distribution function Φ.

Part of the integrand —

$$\phi(s) = \Phi\left[\sqrt{n}\left(z_{R_c} - s\, z_{R^*}\right)\right] \tag{6}$$

has an abrupt behavior at the point $s^* = z_{R_c} / z_{R^*}$ as n becomes large. Fig. (2) indicates this behavior.

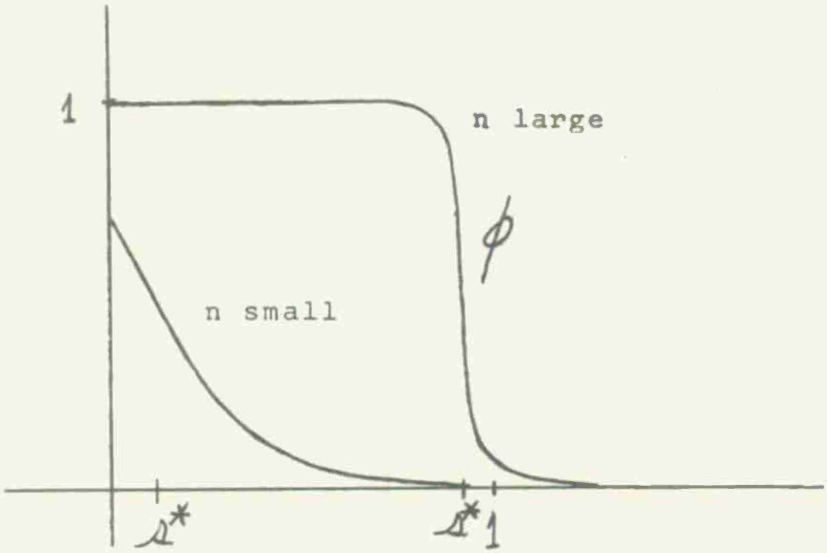


Figure 2

This behavior at s* behooves one to see that the quadrature formula used to perform the integration evaluates the integrand at s*. A three point Gaussian quadrature formula is used in a composite manner to evaluate the integral in Eqn. (1). The principle of successive consistency is used to examine the accuracy of the solution to Eqn. (1); i.e., the integral is evaluated with a successively smaller interval size until the solutions to equation (1) become consistent. The only remaining aspect of the problem is the evaluation of the constant in equation (1).

$$K = \frac{(1-c)\Gamma\left(\frac{n-1}{2}\right)}{2\left(\frac{n}{2}\right)^{\frac{n-1}{2}}} \tag{7}$$

if n is even,

$$K = \frac{(1-c)\sqrt{\frac{\pi n}{2}}}{n^{\frac{n}{2}}(n-1)} \prod_{i=1}^{\frac{n}{2}} (2i-1) \tag{8}$$

if n is odd,

$$K = \left(\frac{n-1}{2}\right)! \left(\frac{2}{n}\right)^{\frac{n-1}{2}} \left(\frac{1-c}{n-1}\right) \tag{9}$$

Expressions (8) and (9) are easily derived using the recursion formula for the gamma function:

$$\Gamma(x) = (x-1)\Gamma(x-1) \tag{10}$$

4. DESCRIPTION OF COMPUTER PROGRAM

A. Main

Significant variable names:

N = sample size

NR = no. of confidenced reliabilities

NIT = no. of iterations for obtaining consistency in results

R = RC = confidenced reliability

NINT = no. of intervals between zero and s* for composite integration

C = confidence level

FRE = fractional error tolerated in solving nonlinear equation

SL = search length for locating first change of sign in nonlinear equation solver (subroutine ROOMID)

CONST = constant in Eqn (1)

ZOMR = z_{1-R_c}

Z = z_{1-R^*}

USTAR = 1 - R*

In general, the main program reads in the necessary data, computes z_{1-R_c} using ROOMID and ZORC, then uses ROOMID and RTF to calculate z_{1-R^*}.

B. FUNCTION RTF(Z)

Significant Variable names:

SCRIT = $z_{1-R_c} / z_{1-R^*} = s^*$

H = interval size

RTF is the function described by Eqn. (1) (a function of z_{R^*}). The tail of the integral $(s > s^*)$ is computed first, using QUAD until the contribution to the integral becomes insignificant. GLAG is then used to squeeze the last drop, if any, out of the tail. The integral for $s \leq s^*$ is then computed using QUAD.

C. FUNCTION F (S)

F computes the integrand in Eqn. (1).

D. FUNCTION ZORC (X)

ZORC (X) = $\Phi(x) + R_c - 1.$

ZORC is used to calculate z_{1-R_c}

E. QUAD (A, B, AR)

QUAD evaluates the integral of F from A to B using three point Gauss-Legendre quadrature.

F. GLAG (A, AR)

GLAG evaluates the integral of F from A to infinity using five point Gauss-Laguerre quadrature.

G. CON (C, N, CONST)

CON evaluates the constant term in Eqn. (1).

H. FUNCTION DN (X)

DN is the normal distribution function Φ.

I. FUNCTION PINT (X)

PINT calculates Φ for large negative arguments.

J. ROOMID (G, X, SL, FRE)

ROOMID solves the equation: G (X) = 0 using the midpoint method. X is the initial guess at the root; SL is the search length. ROOMID assumes that SL will point in the true direction of the root; i.e., if X initially overestimates the true root, SL must be negative.

APPENDIX

Use of Tables:

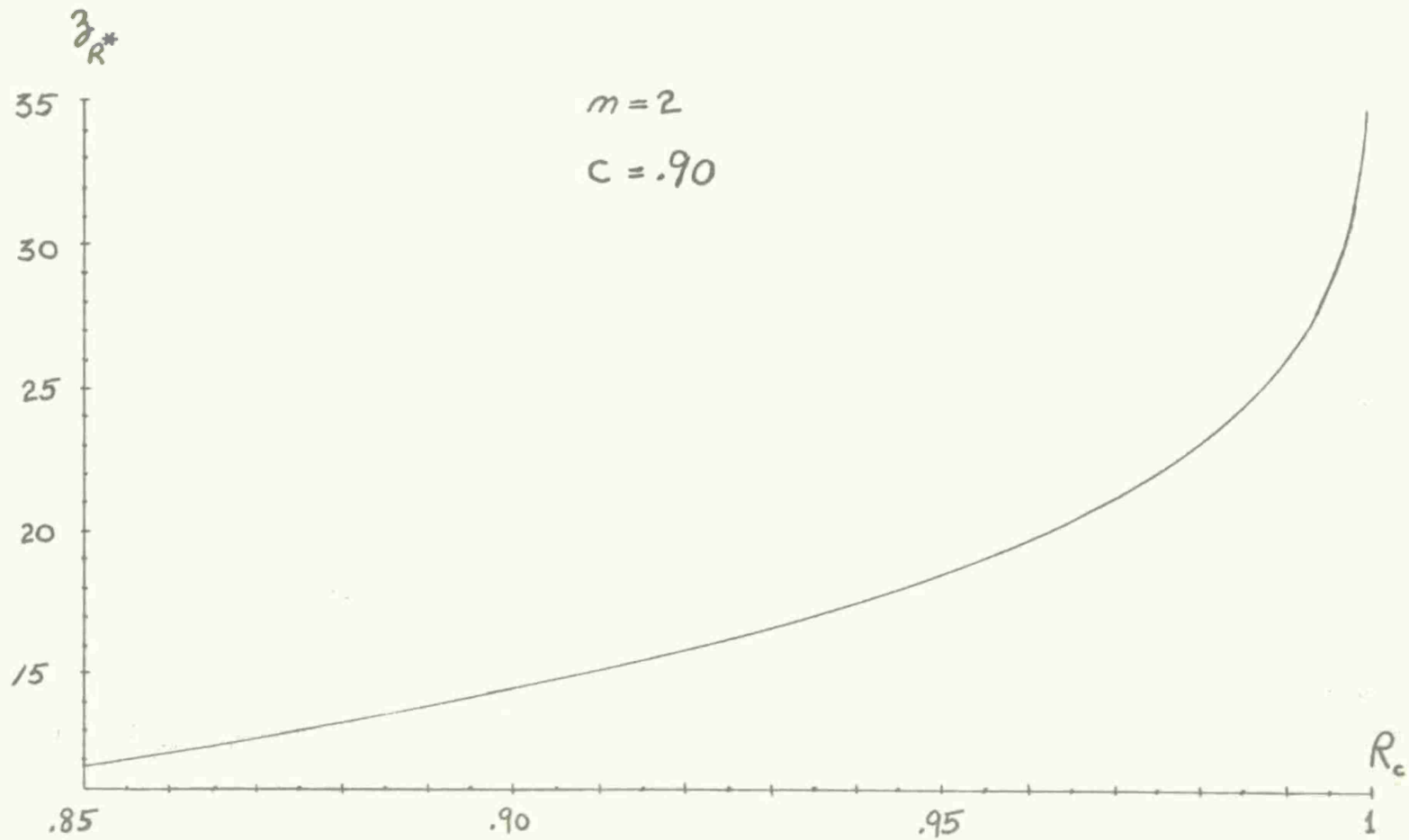
The entries in the body of the tables give z_{R^*} for a given sample size n and confidenced reliability R_c. Eqns. (3) and (5) are used to calculate normal and log-normal mission life respectively. If mission life is the given quantity and confidenced reliability is desired, one could use Lagrangian interpolation, but the simplest thing to do would be to draw a graph of R_c versus z_{R^*} for the desired n. An example is given for n = 2.

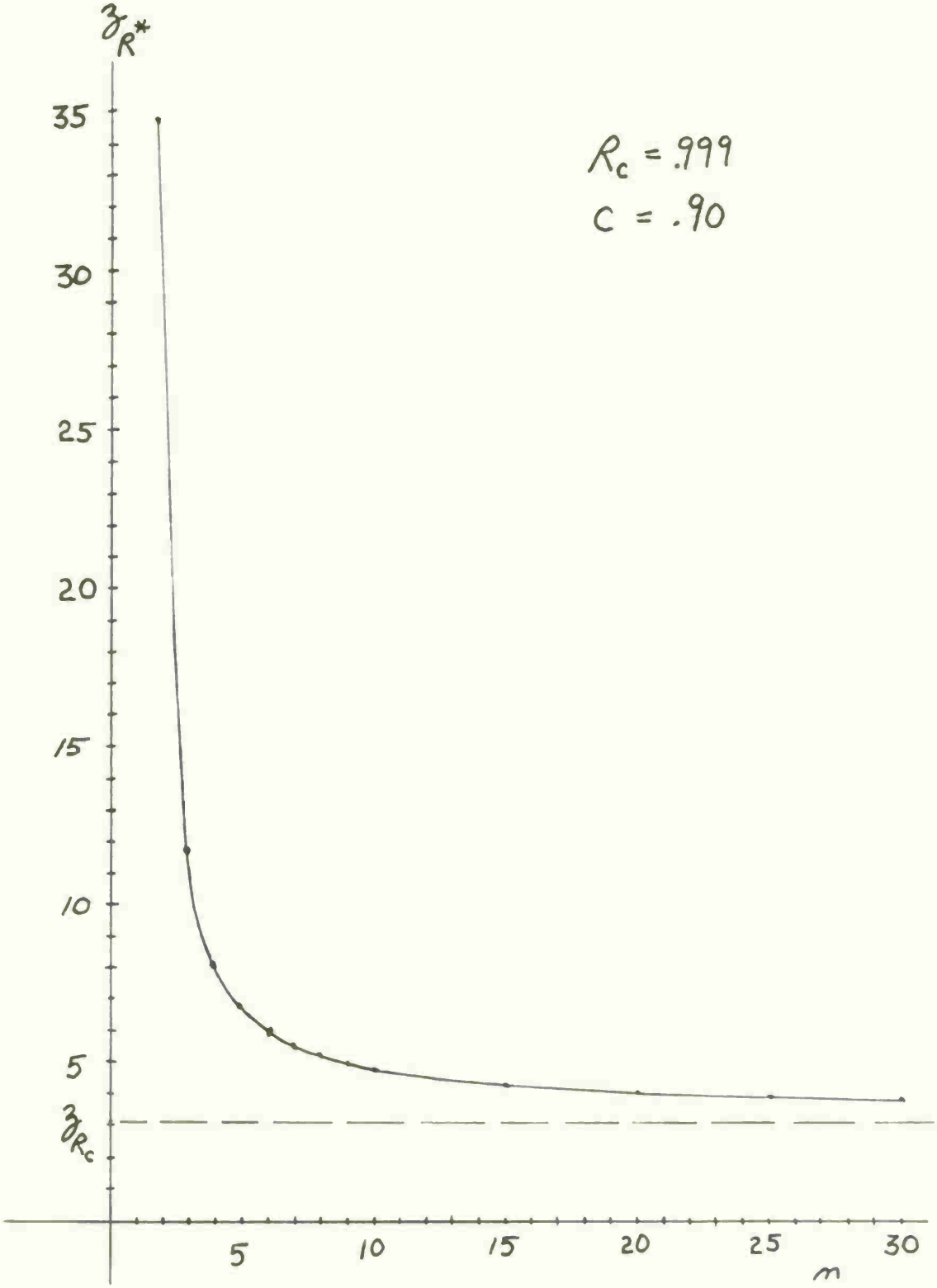
A graph of z_{R^*} versus n is included for R_c = .999 and C = .90. This graph indicates that a considerably rapid increase in information is obtained by increasing n from two to five, while increasing n beyond 10 produces information at a very slow rate.

Finally, it must be noted that maximim likelihood (not unbiased) parameter estimates are to be used with these tables.

R_c	n							C=90%					
	2	3	4	5	6	7	8	9	10	15	20	25	30
.999	34.764	11.820	8.232	6.833	6.086	5.619	5.297	5.060	4.879	4.363	4.113	3.962	3.859
.995	28.972	9.911	6.914	5.742	5.115	4.722	4.451	4.252	4.099	3.663	3.451	3.322	3.235
.99	26.163	8.990	6.280	5.217	4.647	4.290	4.044	3.862	3.723	3.325	3.131	3.013	2.933
.975	22.042	7.647	5.354	4.451	3.966	3.661	3.450	3.294	3.174	2.831	2.664	2.562	2.492
.95	18.512	6.505	4.569	3.801	3.387	3.126	2.944	2.811	2.707	2.411	2.265	2.176	2.115
.925	16.232	5.772	4.064	3.383	3.015	2.781	2.619	2.499	2.407	2.139	2.008	1.927	1.872
.90	14.500	5.215	3.681	3.066	2.732	2.520	2.372	2.262	2.177	1.932	1.811	1.737	1.685
.875	13.083	4.760	3.367	2.806	2.500	2.305	2.168	2.067	1.989	1.762	1.649	1.579	1.532
.85	11.877	4.371	3.099	2.583	2.300	2.120	1.994	1.900	1.827	1.615	1.509	1.444	1.399

R_c	n												C=95%
	2	3	4	5	6	7	8	9	10	15	20	25	30
.999	69.687	16.971	10.64	8.387	7.243	6.548	6.080	5.742	5.485	4.769	4.430	4.228	4.091
.995	58.084	14.241	8.947	7.058	6.097	5.512	5.118	4.832	4.615	4.010	3.722	3.550	3.434
.99	52.458	12.924	8.132	6.419	5.545	5.014	4.654	4.394	4.196	3.644	3.381	3.223	3.116
.975	44.205	11.006	6.945	5.488	4.742	4.288	3.980	3.757	3.586	3.110	2.883	2.746	2.653
.95	37.137	9.377	5.940	4.699	4.062	3.672	3.407	3.215	3.068	2.656	2.458	2.339	2.258
.925	32.573	8.331	5.295	4.193	3.625	3.276	3.040	2.867	2.735	2.364	2.185	2.076	2.003
.90	29.107	7.539	4.806	3.809	3.293	2.976	2.760	2.603	2.482	2.141	1.976	1.876	1.808
.875	26.273	6.891	4.406	3.495	3.022	2.730	2.531	2.386	2.274	1.958	1.804	1.711	1.647
.85	23.860	6.338	4.064	3.226	2.789	2.519	2.335	2.199	2.096	1.800	1.657	1.569	1.509


z_{R^*}
35
30
25
20
15
$m = 2$
$c = .90$
R_c
.85
.90
.95
1


z_{R^*}
35
30
25
20
15
10
5
z_{R_c}
5
10
15
20
25
30
m
$R_c = .999$
$C = .90$

```
100 DIMENSION R(50)
110 COMMON RC,CONST,N,RN,ZOMR,SQN,RNO2
120 COMMON NM2,ZZ,RINT
130 COMMON S2PI,NINT(10),IT
140 EXTERNAL ZORC,RTF
150 CALL OPENF(1,"TBL4")
160 READ(1,),N,NR,NIT
170 READ(1,),(R(I),I=1,NR)
180 READ(1,),(NINT(I),I=1,NIT)
190 READ(1,),C,FRE,SL
200 PRINT 500,N,C
210 500 FORMAT(14HNO. OF POINTS=,I3//17HCONFIDENCE LEVEL=,F5.3//)
220 CALL CON(C,N,CONST)
230 PRINT 600,CONST
240 600 FORMAT(6HCONST=,E16.8/)
250 RN=N
260 SQN=SQRT(RN)
270 PI=3.1415927
280 S2PI=SQRT(2.*PI)
290 RNO2=RN/2.
300 NM2=N-2
310 DO 1 IR=1,NR
320 SLL=SL
330 RC=R(IR)
340 ZOMR=0.
350 CALL ROOMID(ZORC,ZOMR,-2.,FRE)
360 PRINT 100,RC
370 100 FORMAT(24HCONFIDENCED RELIABILITY=,F7.5/)
380 PRINT 200,ZOMR
390 200 FORMAT(8HZ(1-RC)=,E16.8/)
400 Z=ZOMR
410 DO 1 IIT=1,NIT
420 RINT=NINT(IIT)
430 IT=IIT
440 CALL ROOMID(RTF,Z,SLL,FRE)
450 ZSTAR=-Z
460 PRINT 300,ZSTAR
470 300 FORMAT(9HZ(RSTAR)=,E16.8/)
480 USTAR=DN(Z)
490 PRINT 400,USTAR
500 400 FORMAT(6HUSTAR=,E16.8/)
510 SLL=.01*Z
520 Z=Z-SLL
530 1 CONTINUE
540 END
550C
```

```
570 FUNCTION RTF(Z)
580 COMMON RC,CONST,N,RN,ZOMR,SQN,RNO2
590 COMMON NM2,ZZ,RINT
600 COMMON S2PI,NINT(10),IT
610 ZZ=Z
620 SCRIT=ZOMR/Z
630 AREA1=0.
640 H=SCRIT/(RINT-.5)
650 A=SCRIT+.5*H
660 1 B=A+H
670 CALL QUAD(A,B,AR)
680 AREA2=AREA1+AR
690 IF(AREA2-AREA1)3,3,2
700 2 AREA1=AREA2
710 A=B
720 GO TO 1
730 3 CALL GLAG(A,AR)
740 AREA=AREA1+AR
750 NNT=NINT(IT)
760 DO 4 I=1,NNT
770 RI=I
780 A=(RI-1.)*H
790 B=A+H
800 CALL QUAD(A,B,AR)
810 AREA=AREA+AR
820 4 CONTINUE
830 RTF=AREA-CONST
840 RETURN
850 END
860C
870C
880 FUNCTION F(S)
890 COMMON RC,CONST,N,RN,ZOMR,SQN,RNO2
900 COMMON NM2,ZZ,RINT
910 ARGPH=SQN*(S*ZZ-ZOMR)
920 PHI=DN(ARGPH)
930 F=PHI*S**NM2*EXP(-RNO2*S*S)
940 RETURN
950 END
960C
970C
980 FUNCTION ZORC(X)
990 COMMON RC
1000 ZORC=DN(X)+RC-1.
1010 RETURN
1020 END
1030C
```

```
1040C
1050 SUBROUTINE QUAD(A,B,AR)
1060 BMA2=(B-A)/2.
1070 X1=.77459667
1080 A1=BMA2*(X1+1.)+A
1090 A2=BMA2*(-X1+1.)+A
1100 A0=(B+A)/2.
1110 G1=F(A1)
1120 G2=F(A2)
1130 G0=F(A0)
1140 AR=BMA2*(5.*G1+8.*G0+5.*G2)/9.
1150 RETURN
1160 END
1170C
1180C
1190 SUBROUTINE GLAG(A,AR)
1200 DIMENSION X(5),WEX(5)
1210C PROGRAM COMPUTES INTEGRAL FROM A TO INFINITY OF F(X)
1220C USING 5 POINT GAUSS-LAGUERRE QUADRATURE
1230 X(1)=.26356032
1240 X(2)=1.4134031
1250 X(3)=3.5964258
1260 X(4)=7.0858100
1270 X(5)=12.640801
1280 WEX(1)=.67909404
1290 WEX(2)=1.6384879
1300 WEX(3)=2.7694432
1310 WEX(4)=4.3156569
1320 WEX(5)=7.2191864
1330 AR=0.
1340 DO 1 I=1,5
1350 A1=X(I)+A
1360 G=F(A1)
1370 AR=AR+G*WEX(I)
1380 1 CONTINUE
1390 RETURN
1400 END
1410C
```

```
1430 SUBROUTINE CON(C,N,CONST)
1440C PROGRAM COMPUTES (1-C)GAM((N-1)/2)/(2(N/2)**((N-1)/2))
1450 RN=N
1460 N2=N/2
1470 RN02=RN/2.
1480 RN2=N2
1490 IF(RN02-RN2)3,1,3
1500 1 PI=3.1415927
1510 P=1.
1520 DO 2 I=1,N2
1530 RI=I
1540 P=P*(2.*RI-1.)
1550 2 CONTINUE
1560 CONST=P/((2.*RN2-1.)*(2.*RN2)**N2)*(1.-C)*SQRT(PI*RN2)
1570 RETURN
1580 3 P=1.
1590 DO 4 I=1,N2
1600 RI=I
1610 P=P*RI
1620 4 CONTINUE
1630 CONST=P*2.**(N2-1)/(RN2*(2.*RN2+1.)**N2)*(1.-C)
1640 RETURN
1650 END
1660C
1670C
1680 FUNCTION DN(X)
1690 IF(X+5.)1,1,2
1700 1 DN=PINT(X)
1710 RETURN
1720 2 IF(X-6.)4,3,3
1730 3 DN=1.
1740 RETURN
1750 4 AX=ABS(X)
1760 S2PI=2.5066283
1770 P=.2316419
1780 B1=.31938153
1790 B2=-.35656378
1800 B3=1.7814779
1810 B4=-1.8212560
1820 B5=1.3302744
1830 T=1./(1.+P*AX)
1840 S=T*(B1+T*(B2+T*(B3+T*(B4+T*B5))))
1850 DN=S/S2PI*EXP(-.5*X*X)
1860 IF(X)5,5,6
1870 5 RETURN
1880 6 DN=1.-DN
1890 RETURN
1900 END
1910C
1920C
```

```
1930 FUNCTION PINT(A)
1940 A2=A*A
1950 A3=A*A2
1960 S1=(1.-A2)/A3
1970 S2=S1
1980 AI1=1./A3
1990 DO 1 I=2,200
2000 RI=I
2010 AI2=-(2.*RI+1.)*AI1/A2
2020 IF(ABS(AI2)-ABS(AI1))2,4,4
2030 2 S2=S2+AI2
2040 IF(S1-S2)3,4,3
2050 3 S1=S2
2060 AI1=AI2
2070 1 CONTINUE
2080 4 C=2.5066283
2090 PINT=EXP(-A2/2.)*S2/C
2100 RETURN
2110 END
2120C
2130C
2140 SUBROUTINE ROOMID(G,X,SL,FRE)
2150 EXTERNAL G
2160 X1=X
2170 F1=G(X1)
2180 3 X2=X1+SL
2190 F2=G(X2)
2200 IF(F1*F2)5,5,2
2210 2 X1=X2
2220 F1=F2
2230 GO TO 3
2240 5 X=.5*(X1+X2)
2250 FX=G(X)
2260 IF(FX*F1)7,13,6
2270 6 X1=X
2280 F1=FX
2290 GO TO 10
2300 7 X2=X
2310 10 A1=ABS(X1)
2320 A2=ABS(X2)
2330 IF(A1-A2)8,8,9
2340 8 AMIN=A1
2350 GO TO 11
2360 9 AMIN=A2
2370 11 PE=.5*ABS(X2-X1)/AMIN
2380 IF(PE-FRE)12,12,5
2390 12 X=.5*(X1+X2)
2400 13 FX=F(X)
2410 RETURN
2420 END
```

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13. ABSTRACT

Small sample size tables are presented which facilitate reliability--mission life calculations at a given confidence level. The tables are calculated using the exact sampling distribution of the normal reliability estimator. A computer program is included which will enable one to calculate more extensive tables for different sample sizes and confidence levels.

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Reliability						
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Nonlinear equations						

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Small sample size tables are presented which facilitate reliability--mission life calculations at a given confidence level. The tables are calculated using the exact sampling distribution of the normal reliability estimator. A computer program is included which will enable one to calculate more extensive tables for different sample sizes and confidence levels.

Reliability

Confidence interval

Neyman

Estimator

Exact sampling distribution

Gaussian quadrature

Nonlinear equations

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