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Project Title: ***Level of Information and Reliability Estimate for a Canister***

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This notebook documents the work being done in support of Appendix B for the Interim Staff Guidance HLWRS-ISG-02, Preclosure Safety Analysis – Level of Information and Reliability Estimation developed by the Division of High-Level Waste Repository Safety (NRC). Microsoft® Excel 2002 is used to perform the calculations and MATLAB 7.0.1 code is used to generate the plots ("MATLAB User's Manual", Version 7.0.1. The MathWorks, Inc., Massachusetts, 2004).

The qualifications required for the staff supporting this work are as follows:

(i) Probability, Reliability and Statistical Methods;
(ii) Mechanical and Civil Engineering.

Date: July 31, 2006
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Reliability Estimate of a Canister – Example 1

An approach is presented to estimate the probability of failure for a canister when dropped from a specific height during handling operations. The canister failure is defined when the stress intensities, predicted using an elastic analysis, exceed ultimate strength of the material. Alternative methods for estimating the reliability of a canister may include non-linear analysis and the strain failure criterion.

Methodology and Assumptions

1. The canister is assumed to have been designed in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME B&PV), Section III, Division 1, Subsection NB, ASME International, 2001.

2. The canister is assumed to be fabricated from Type 304 stainless steel, with the following material properties at room temperature [ASME B&PV Code, Section II, Part D, Table 2A, ASME International, 2001.]

Table 1.

Material Properties	Allowable Values
Ultimate Tensile Strength, σ_u	517 *MPa* (75 *ksi*)
Yield Strength, σ_y	207 *MPa* (30 *ksi*)
Design Stress Intensity, S_m	138 *MPa* (20 *ksi*)

3. The approach is based on methods used for assessment of structural reliability [Halgar, A., Mahadevan, S., *Probability, Reliability, and Statistical Methods in Engineering Design.* John Wiley and Sons, Inc., New York, 2000.] A measure of reliability of the canister in the context of a design is the safety factor which is a function of the load or demand on the system from the drop impact and the resistance or capacity of the system. The failure of the system is assumed to occur when the demand is greater than or equal to the capacity or, alternatively, when the ratio of capacity to demand is less than or equal to 1. Thus, the probability of failure, P_f, is given by probability that the capacity is less than the demand, as given by the following equation:

$$P_f = P(C \le D) \text{ or } P_f = P(S \le 1) \tag{1}$$

where, C is the capacity, D is the demand, and

$$S = C/D \tag{2}$$

C and D are random in nature and the associated variability or uncertainty associated with it is represented by probability density functions $f_C(x)$ and $f_D(x)$ respectively. It must be noted C and D can be function of different engineering parameters. Combining the variability in capacity and

demand using equation 2, a probability density function can be developed for S as $f_S(s)$. The probability of failure, defined by $S \leq 1$, is calculated by integrating $f_S(s)$ for s from 0 to 1 as shown in equation 3.

$$P_f = \int_0^1 f_S(s)ds \tag{3}$$

where, $f_S(s)$ is the probability density function of S.

4. The capacity, C, is defined by the ultimate tensile strength, σ_u. Therefore, the uncertainty in the capacity is based only on the variability of σ_u.

5. The demand, D, is expressed as the maximum stress intensity in the canister from the vertical drop impact or other type of loading.

Demand

The demand parameter for this analysis corresponds to the performance requirements of Level D Service Limits for accidental condition load combinations in ASME B&PV Code, Section III, Division 1, NB3225, ASME International, 2001. A Level D service limit, defined in NB 2142.4, permits gross general deformations with some consequent loss of dimensional stability and damage requiring repair. The acceptance criteria for design for Level D Service Limits is given by

Table 2.

Stress Category	Level D Limiting Criteria
Primary Membrane Stress Intensity, P_m	Minimum of $2.4S_m$ and $0.7\sigma_u$
Primary Membrane (Local or General) (P_L) plus Primary Bending (P_b) Stress Intensity, i.e. P_L+P_b	150% of P_m

From Table 1 and 2:

$$\begin{aligned} P_L+P_b &= 1.5\times\min(2.4S_m, 0.7\sigma_u) \\ &= 1.5\times\min(2.4\times138\ MPa, 0.7\times517\ MPa) \\ &= 1.5\times\min(331\ MPa, 362\ MPa) \\ &= 1.5\times331\ MPa \\ &= 497\ MPa. \end{aligned}$$

Therefore, the demand in the canister from the hypothetical drop event is assumed to be 497 *MPa* (72 *ksi*), which is the allowable Level D stress intensity for the combined primary membrane (local or general) and bending. Thus the ratio of the ASME B&PV Code Level D allowable stress intensity to predicted maximum stress intensity, or demand, is 1.0. Considering the uncertainties in the capacity of the material, C, the probability of failure is estimated corresponding to the demand value of 497*MPa* (72 *ksi*). Additional demand values are 473 and 453 *MPa* (69 and 66 *ksi*) that correspond to 1.05 and 1.1 ratio.

Capacity

Information on variability of the ultimate tensile strength of Type 304 stainless steel is obtained from the test data discussed by McCoy and Waddell [McCoy H.E., Jr. and Waddell R.D., *Mechanical Properties of Several Products from a Single Heat of Type 304 Stainless Steel*, Journal of Engineering Materials and Technology, Vol. 97, 1975.] The ultimate tensile strength for "As Received" category varied from 538 to 662 *MPa* (78.0 to 96.0 *ksi*) and is shown below.

Table 3.

Test ##	Ultimate Tensile Strength, *ksi*	Test ##	Ultimate Tensile Strength, *ksi*	Test ##	Ultimate Tensile Strength, *ksi*
1	89.4	11	78.8	21	82.4
2	89.2	12	80.6	22	83.5
3	87.0	13	85.6	23	85.4
4	87.9	14	85.2	24	84.5
5	87.0	15	85.2	25	84.6
6	85.9	16	86.4	26	96.0
7	85.2	17	89.8	27	93.3
8	83.8	18	88.1	28	86.5
9	84.0	19	89.9	29	86.5
10	81.6	20	82.8		

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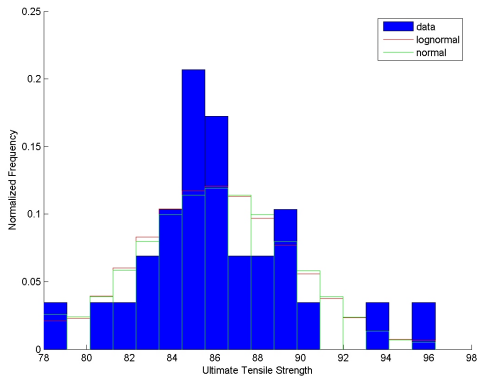
The Chi-square Goodness-of-fit test of the ultimate tensile strength data for "As Received" category (refer to Table 3) showed that the lognormal distribution should be used ($\chi^2_{log} < \chi^2_{norm}$): for the lognormal distribution $\chi^2_{log}=0.3932$ and for the normal distribution $\chi^2_{norm}=0.4429$.



The following MatLab® Code was used to perform the Chi-square Goodness-of-fit test

```
%++++++++++++++++++++++++++++++++++++++++++++
% BEGINNING
%++++++++++++++++++++++++++++++++++++++++++++
clear all
close all
clc

x = [78.8 80.6 81.6 82.4 82.8...
    83.5 83.8 84.0 84.5 84.6...
    85.2 85.2 85.2 85.4 85.6...
    85.9 86.4 86.5 86.5 87.0...
    87.0 87.9 88.1 89.2 89.4...
    89.8 89.9 93.3 96.0];

%-------------------------------------------------------------------------
% creating bins
%-------------------------------------------------------------------------
n = length(x);              % number of data points

% dividing data into intervals (bit limits)
X = [78.0000 79.0766 80.1531 81.2297 82.3063 83.3828 84.4594...
    85.5360 86.6126 87.6891 88.7657 89.8423 90.9188 91.9954...
    93.0720 94.1485 95.2251 96.3017];

% number of events in each bin
N = [1 0 1 1 2 3 6 5 2 2 3 1 0 0 1 0 1];

k = length(N);
```

```
%-----------------------------------------------------------------------
% calculating observed frequency
%-----------------------------------------------------------------------

O = N./n;                    % observed frequency

%-----------------------------------------------------------------------
% calculating theoretical frequency
%-----------------------------------------------------------------------
[mu_hat,sigma]=normfit(x); % parameters of normal distribution
stats=lognfit(x);                % parameters of lognormal distribution

mu = stats(1,1);          % mean for normal distribution
beta = stats(1,2);        % standard deviation for normal distribution

% from -inf to 1st point
E_log(1) = logncdf(X(2),mu,beta);              % theoretical frequency for lognormal
E_norm(1) = normcdf(X(2),mu_hat,sigma);  % theoretical frequency for normal

% between 1st and last points
for i=2:1:k-1
   E_log(i) = logncdf(X(i+1),mu,beta)...
            -logncdf(X(i),mu,beta);              % theoretical frequency for lognormal
   E_norm(i) = normcdf(X(i+1),mu_hat,sigma)...
            -normcdf(X(i),mu_hat,sigma);      % theoretical frequency for normal
end

% from last point to +inf
E_log(k) = 1 - logncdf(X(k),mu,beta);             % theoretical frequency for lognormal
E_norm(k) = 1 - normcdf(X(k),mu_hat,sigma); % theoretical frequency for normal

%-----------------------------------------------------------------------
% calculating chi-square
%-----------------------------------------------------------------------
Chi_log = sum((O-E_log).^2./E_log)       % for lognormal
Chi_norm = sum((O-E_norm).^2./E_norm)    % for normal

%-----------------------------------------------------------------------
% plotting
%-----------------------------------------------------------------------
figure(1)
hold on
```

```
for i=1:1:k
   % plotting observed frequency
   fill([X(i), X(i), X(i+1), X(i+1)],[0, O(i), O(i), 0], 'b');
   % plotting theoretical frequency
   plot([X(i), X(i), X(i+1), X(i+1)],[0, E_log(i), E_log(i), 0], 'r');
   plot([X(i), X(i), X(i+1), X(i+1)],[0, E_norm(i), E_norm(i), 0], 'g');
end

for i=1:1:k
   mid_point(i) = (X(i) + X(i+1))./2;
end

plot(mid_point,E_log,'r--','LineWidth',2);
plot(mid_point,E_norm,'g--','LineWidth',2);
ylabel('Normalized Frequency')
xlabel('Ultimate Tensile Strength')

%++++++++++++++++++++++++++++++++++++++++++++
% END
%++++++++++++++++++++++++++++++++++++++++++++
```

The following calculations were performed in Microsoft® Excel:

Table 4.

Analysis of the Test Data, ksi	
Mean	85.95357143
Standard Error	0.679547822
Median	85.5
Mode	85.2
Standard Deviation	3.59582908
Sample Variance	12.92998677
Kurtosis	1.575175061
Skewness	0.742498844
Range	17.2
Minimum	78.8
Maximum	96
Sum	2406.7
Count	28
Largest(1)	96
Smallest(1)	78.8
Confidence Level(95.0%)	1.394316024

Analysis of the Log of Test Data	
Mean	4.452976911
Standard Error	0.007813601
Median	4.448515692
Mode	4.445001434
Standard Deviation	0.041345693
Sample Variance	0.001709466
Kurtosis	1.324213733
Skewness	0.57503942
Range	0.197435195
Minimum	4.366912997
Maximum	4.564348191
Sum	124.6833535
Count	28
Largest(1)	4.564348191
Smallest(1)	4.366912997
Confidence Level(95.0%)	0.016032175

The median, m_c, and logarithmic standard deviation, β, for the ultimate tensile strength were estimated to be 589.5 *MPa* (85.4 *ksi*) and 0.0413, respectively.

Probability of Failure

Based on the variability in the capacity parameter and a single demand value, the probability of failure was calculated using Microsoft® Excel (see D:\SientificNotes\SN814E-AppendixB.xls for more details).

Table 5

Probability of Failure based on Data analysis, *MPa*

Capacity (MPa)	Median	589.5	Mean=ln(median)	6.379275
β		0.0413		
Code Allowable	MPa	497	497	497
Demand		497	473	452
Ratio		1	1.050739958	1.099558
S	Median	1.186117	1.246300211	1.304204
	β	0.0413	0.0413	0.0413
	Mean=ln(median)	0.170685	0.220179331	0.265593

		D=497		D=473		D=452	
C	CDF of C	S=C/D	CDF of S	S=C/D	CDF of S	S=C/D	CDF of S
450	3.13E-11	0.905	3.13E-11	0.951	3.13E-11	0.996	3.13E-11
451	4.47E-11	0.907	4.47E-11	0.953	4.47E-11	0.998	4.47E-11
452	6.38E-11	0.909	6.38E-11	0.956	6.38E-11	1.000	6.38E-11
453	9.05E-11	0.911	9.05E-11	0.958	9.05E-11	1.002	9.05E-11
454	1.28E-10	0.913	1.28E-10	0.960	1.28E-10	1.004	1.28E-10
455	1.81E-10	0.915	1.81E-10	0.962	1.81E-10	1.007	1.81E-10
456	2.54E-10	0.918	2.54E-10	0.964	2.54E-10	1.009	2.54E-10
457	3.55E-10	0.920	3.55E-10	0.966	3.55E-10	1.011	3.55E-10
458	4.95E-10	0.922	4.95E-10	0.968	4.95E-10	1.013	4.95E-10
459	6.89E-10	0.924	6.89E-10	0.970	6.89E-10	1.015	6.89E-10
460	9.54E-10	0.926	9.54E-10	0.973	9.54E-10	1.018	9.54E-10
461	1.32E-09	0.928	1.32E-09	0.975	1.32E-09	1.020	1.32E-09
462	1.81E-09	0.930	1.81E-09	0.977	1.81E-09	1.022	1.81E-09
463	2.49E-09	0.932	2.49E-09	0.979	2.49E-09	1.024	2.49E-09
464	3.40E-09	0.934	3.40E-09	0.981	3.40E-09	1.027	3.40E-09
465	4.63E-09	0.936	4.63E-09	0.983	4.63E-09	1.029	4.63E-09
466	6.29E-09	0.938	6.29E-09	0.985	6.29E-09	1.031	6.29E-09
467	8.51E-09	0.940	8.51E-09	0.987	8.51E-09	1.033	8.51E-09
468	1.15E-08	0.942	1.15E-08	0.989	1.15E-08	1.035	1.15E-08
469	1.54E-08	0.944	1.54E-08	0.992	1.54E-08	1.038	1.54E-08
470	2.07E-08	0.946	2.07E-08	0.994	2.07E-08	1.040	2.07E-08
471	2.76E-08	0.948	2.76E-08	0.996	2.76E-08	1.042	2.76E-08
472	3.68E-08	0.950	3.68E-08	0.998	3.68E-08	1.044	3.68E-08
473	4.89E-08	0.952	4.89E-08	1.000	4.89E-08	1.046	4.89E-08
474	6.47E-08	0.954	6.47E-08	1.002	6.47E-08	1.049	6.47E-08

475	8.54E-08	0.956	8.54E-08	1.004	8.54E-08	1.051	8.54E-08
476	1.12E-07	0.958	1.12E-07	1.006	1.12E-07	1.053	1.12E-07
477	1.47E-07	0.960	1.47E-07	1.008	1.47E-07	1.055	1.47E-07
478	1.92E-07	0.962	1.92E-07	1.011	1.92E-07	1.058	1.92E-07
479	2.51E-07	0.964	2.51E-07	1.013	2.51E-07	1.060	2.51E-07
480	3.26E-07	0.966	3.26E-07	1.015	3.26E-07	1.062	3.26E-07
481	4.22E-07	0.968	4.22E-07	1.017	4.22E-07	1.064	4.22E-07
482	5.45E-07	0.970	5.45E-07	1.019	5.45E-07	1.066	5.45E-07
483	7.02E-07	0.972	7.02E-07	1.021	7.02E-07	1.069	7.02E-07
484	9.02E-07	0.974	9.02E-07	1.023	9.02E-07	1.071	9.02E-07
485	1.15E-06	0.976	1.15E-06	1.025	1.15E-06	1.073	1.15E-06
486	1.47E-06	0.978	1.47E-06	1.027	1.47E-06	1.075	1.47E-06
487	1.88E-06	0.980	1.88E-06	1.030	1.88E-06	1.077	1.88E-06
488	2.38E-06	0.982	2.38E-06	1.032	2.38E-06	1.080	2.38E-06
489	3.01E-06	0.984	3.01E-06	1.034	3.01E-06	1.082	3.01E-06
490	3.80E-06	0.986	3.80E-06	1.036	3.80E-06	1.084	3.80E-06
491	4.78E-06	0.988	4.78E-06	1.038	4.78E-06	1.086	4.78E-06
492	6.00E-06	0.990	6.00E-06	1.040	6.00E-06	1.088	6.00E-06
493	7.51E-06	0.992	7.51E-06	1.042	7.51E-06	1.091	7.51E-06
494	9.38E-06	0.994	9.38E-06	1.044	9.38E-06	1.093	9.38E-06
495	1.17E-05	0.996	1.17E-05	1.047	1.17E-05	1.095	1.17E-05
496	1.45E-05	0.998	1.45E-05	1.049	1.45E-05	1.097	1.45E-05
497	1.79E-05	1.000	1.79E-05	1.051	1.79E-05	1.100	1.79E-05
498	2.21E-05	1.002	2.21E-05	1.053	2.21E-05	1.102	2.21E-05
499	2.72E-05	1.004	2.72E-05	1.055	2.72E-05	1.104	2.72E-05
500	3.35E-05	1.006	3.35E-05	1.057	3.35E-05	1.106	3.35E-05

The failure probability was estimated as follows

Table 6.

Demand (Stress Intensity)	**Safety factor, *S***	**Probability of Failure**
497 *MPa* (72 *ksi*)	1.00	1.8×10^{-5}
473 *MPa* (69 *ksi*)	1.05	4.8×10^{-8}
452 *MPa* (66 *ksi*)	1.10	6.4×10^{-11}

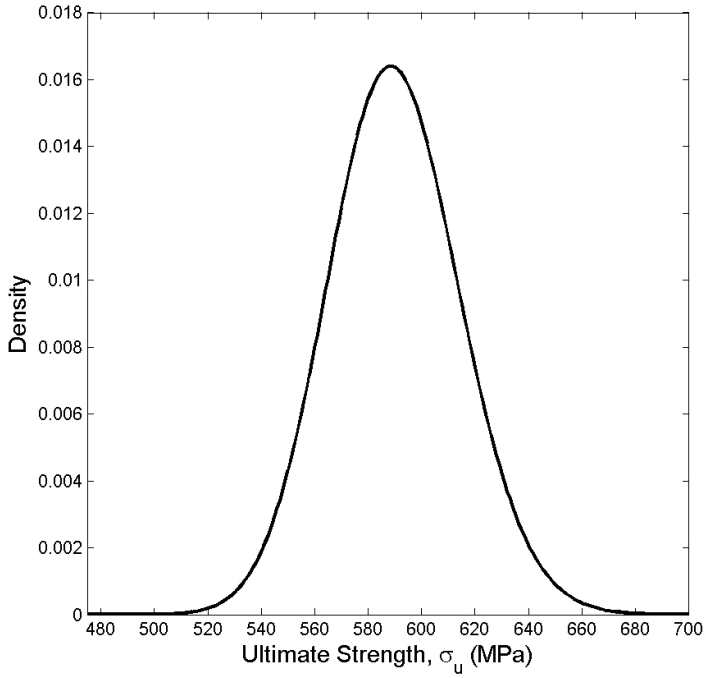


Figure 1. Probability Density Function of the ultimate tensile strength, σ_u.

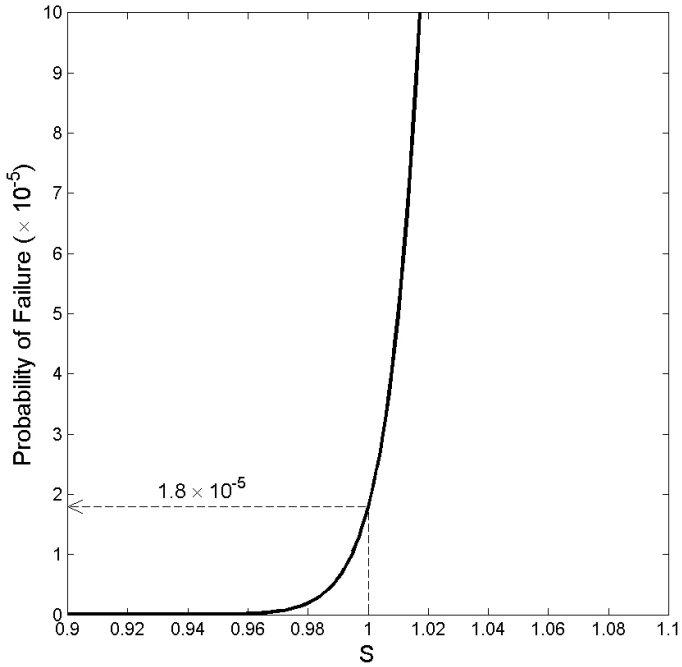


Figure 2. Cumulative Distribution Function of *S*.

The following MatLab® Code was used to generate Figures 1 and 2.

```
%++++++++++++++++++++++++++++++++++++++++++
% BEGINNING
%++++++++++++++++++++++++++++++++++++++++++

clear all
close all
clc

global msf betasf

% median and logarithmic standard deviation
mc = 589.5; % in MPa but 85.4 ksi
betac = 0.0413;

% capacity range
c1 = 475;
c2 = 700;
c = c1:1:c2;

% calculate capacity pdf
fc = lognpdf(c,log(mc),betac);

   figure(1);
   plot(c,fc,'k','LineWidth',2);
   hold on
   axis square;
   xlabel('Ultimate Strength, \sigma_u (MPa)','FontSize',14);
   ylabel('Density','FontSize',14);
   axis([475 700 0 0.018])
   print -djpeg99 PDF % save plot as a jpeg file

D = 497; % in MPa demand = stress intensity

% obtain mean, median and logarithmic standard deviation
betasf = betac;
msf = mc/D;

sf = 0.9:0.001:1.1; % safety factor

% calculate capacity cdf
Fsf = logncdf(sf,log(msf),betasf);
```

```
    figure(2);
    plot(sf,Fsf./1e-5,'k','LineWidth',2);
    hold on
    axis square;
    xlabel('S','FontSize',14);
    ylabel('Probability of Failure (\times 10^{-5})','FontSize',14);
    axis([0.9 1.1 0 10])
    plot([1 1], [0,1.7918], '--k')
    plot([0 1], [1.7918,1.7918], '--k')
    plot([0.90 0.905], [1.7918,1.9018], 'k')
    plot([0.90 0.905], [1.7918,1.6818], 'k')
    text(0.93,2.1, '1.8 \times 10^{-5}', 'Color', 'black','FontSize',12)
    print -djpeg99 SafetyFactorCDF % save plot as a jpeg file

% perform numerical integration (see file 'logcdfsf.m')
pf = quadl(@logpdfsf,0,1)

%++++++++++++++++++++++++++++++++++++++++++++
% END
%++++++++++++++++++++++++++++++++++++++++++++
```

The following function is used in the above MatLab® Code.

```
%++++++++++++++++++++++++++++++++++++++++++++
% BEGINNING
%++++++++++++++++++++++++++++++++++++++++++++

function y = logcdfsf(x)

global msf betasf

y = lognpdf(x,log(msf),betasf); %lognormal pdf

%++++++++++++++++++++++++++++++++++++++++++++
% END
%++++++++++++++++++++++++++++++++++++++++++++
```

Date: October 30, 2006
Entry by: Roman V. Kazban

Reliability Estimate of a Canister – Example 2

The probability of failure can be estimated as follows

$$P_f = P(g < 0)$$

where g is the safety limit state function.

The safety state will be violated if

$$C - D < 0 \text{ or } \frac{C}{D} < 1$$

where C is the capacity and D is the demand. Since C has lognormal distribution and it can not take negative values, the safety limit state function can be written as

$$g = \ln(C) - \ln(D)$$

Then the probability of failure can be estimated as follows [Halgar, A., Mahadevan, S., *Probability, Reliability, and Statistical Methods in Engineering Design.* John Wiley and Sons, Inc., New York, 2000]

$$P_f = 1 - \Phi\left(\frac{\ln\left[\left(\frac{\mu_C}{\mu_D}\right)\sqrt{\frac{1+\delta_D^2}{1+\delta_C^2}}\right]}{\sqrt{\ln\left[\left(1+\delta_C^2\right)\left(1+\delta_D^2\right)\right]}}\right) \tag{4}$$

where Φ is the cumulative distribution function; μ_C is the capacity mean value; μ_D is the demand mean value; δ_C is the capacity coefficient of variation; and δ_D is the demand coefficient of variation.

The coefficient of variation can be estimates as follows

$$\delta_{C,D} = \beta_{C,D} / \mu_{C,D}$$

where β is the logarithmic standard deviation.

For the case when $\delta_{C,D}<0.3$ the Equation 4 can be simplified to

$$P_f = 1 - \Phi\left(\frac{\ln\left(\frac{\mu_C}{\mu_D}\right)}{\sqrt{\delta_C^2 + \delta_D^2}}\right) \quad \text{or} \quad P_f = 1 - \Phi(\chi) \tag{5}$$

For the capacity: the mean μ_C=6.3793 (see Table 5); the logarithmic standard deviation β_C=0.0413; and the coefficient of variation δ_C=0.0065.

For the demand:

Load, *MPa*	μ_D
497 *MPa*	6.2086
473 *MPa*	6.1591
452 *MPa*	6.1137

Also, since the demand is assumed to be constant, the coefficient of variation $\boldsymbol{\delta_D}$**=0.**

Using Equation 5, the probability of failure was estimated as

Load, *MPa*	χ	P_f
497 *MPa*	4.1728	1.51×10^{-5}
473 *MPa*	5.4043	3.26×10^{-8}
452 *MPa*	6.5425	3.04×10^{-11}

Date: January 17, 2006
Entry by: Fernando J. Ferrante

Development of Final Figure 2 in Appendix B, ISG-02

The MATLAB routine *'canisterfigure.m'* was developed to create the final Figure 2 used in Appendix B of ISG-02. It calculates the cumulative distribution function (CDF) for all three cases of safety factor S corresponding to three deterministic levels of demand D, assuming the capacity C follows a lognormal distribution with parameters derived previously in this scientific notebook. The arrows indicating the values of the CDF at which s = 1 (i.e. $P_S(S < 1)$) as shown in ISG-02 were added manually, after the figure is obtained using *'canisterfigure.m'*.

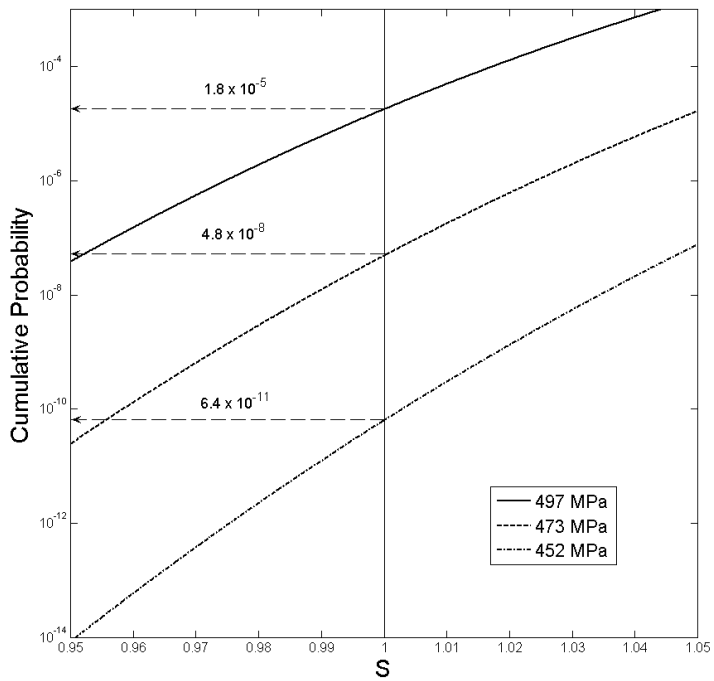


Figure 3: CDF for Safety Factor S

<u>*canisterfigure.m*</u>

```
clear all;

% Demand Value
D = 497;
% Median and Logarithmic Standard Deviation for Capacity
```

```
mc = 589.5;
betac = 0.0413;
% Calculate mean for Capacity
muc = mc*exp(0.5*betac^2);
% Calculate mean, log. std and median for Safety Factor (S = C/D)
mus = muc/D;
betas = betac;
ms = mus*exp(-0.5*betas^2);
% Calculate and plot cumulative distribution function
s = 0:0.0001:2;
Fs = logncdf(s,log(ms),betas);
semilogy(s,Fs,'k','LineWidth',2);
axis([0.95 1.05 10^(-14) 10^(-3)])
hold on

clear all;
% Same as above with different demand value
D = 473;
mc = 589.5;
betac = 0.0413;
muc = mc*exp(0.5*betac^2);
mus = muc/D;
betas = betac;
ms = mus*exp(-0.5*betas^2);
s = 0:0.0001:2;
Fs = logncdf(s,log(ms),betas);
plot(s,Fs,'k--','LineWidth',2);

clear all;
% Same as above with different demand value
D = 452;
mc = 589.5;
betac = 0.0413;
muc = mc*exp(0.5*betac^2);
mus = muc/D;
betas = betac;
ms = mus*exp(-0.5*betas^2);
s = 0:0.0001:2;
Fs = logncdf(s,log(ms),betas);
plot(s,Fs,'k-.','LineWidth',2);
legend('497 MPa','473 MPa','452 MPa')
axis square
% Plot line at s = 1
```

```
plot([1 1],[0 1],'k--')
grid on

xlabel('s','FontSize',22);
ylabel('Cumulative Probability','FontSize',22);
legend('497 MPa','473 MPa','452 MPa')
```

Appendix B

Probability of Failure based on Data analysis

Capacity (Mpa)	Median	588.4		6.377407			
β		0.042	Mean=ln(med				
Code Allowable	MPa	497	497	497	497	497	497
Demand		497	473	452	432	414	398
Ratio		1	1.050739958	1.099558	1.150463	1.200483	1.248744
S	Median	1.183903	1.24397463	1.30177			
	β	0.042	0.042	0.042			
	Mean= ln(median)	0.168817	0.2183116	0.263725			

			D=497		D=473		D=452	
C		CDF of C	S=C/D	CDF of S	S=C/D	CDF of S	S=C/D	CDF of S
	450	8.58E-11	0.905	8.58E-11	0.951	8.58E-11	0.996	8.58E-11
	451	1.21E-10	0.907	1.21E-10	0.953	1.21E-10	0.998	1.21E-10
	452	1.70E-10	0.909	1.70E-10	0.956	1.70E-10	1.000	1.70E-10
	453	2.38E-10	0.911	2.38E-10	0.958	2.38E-10	1.002	2.38E-10
	454	3.33E-10	0.913	3.33E-10	0.960	3.33E-10	1.004	3.33E-10
	455	4.63E-10	0.915	4.63E-10	0.962	4.63E-10	1.007	4.63E-10
	456	6.42E-10	0.918	6.42E-10	0.964	6.42E-10	1.009	6.42E-10
	457	8.87E-10	0.920	8.87E-10	0.966	8.87E-10	1.011	8.87E-10
	458	1.22E-09	0.922	1.22E-09	0.968	1.22E-09	1.013	1.22E-09
	459	1.68E-09	0.924	1.68E-09	0.970	1.68E-09	1.015	1.68E-09
	460	2.29E-09	0.926	2.29E-09	0.973	2.29E-09	1.018	2.29E-09
	461	3.13E-09	0.928	3.13E-09	0.975	3.13E-09	1.020	3.13E-09
	462	4.25E-09	0.930	4.25E-09	0.977	4.25E-09	1.022	4.25E-09
	463	5.76E-09	0.932	5.76E-09	0.979	5.76E-09	1.024	5.76E-09
	464	7.78E-09	0.934	7.78E-09	0.981	7.78E-09	1.027	7.78E-09
	465	1.05E-08	0.936	1.05E-08	0.983	1.05E-08	1.029	1.05E-08
	466	1.40E-08	0.938	1.40E-08	0.985	1.40E-08	1.031	1.40E-08
	467	1.88E-08	0.940	1.88E-08	0.987	1.88E-08	1.033	1.88E-08
	468	2.51E-08	0.942	2.51E-08	0.989	2.51E-08	1.035	2.51E-08
	469	3.33E-08	0.944	3.33E-08	0.992	3.33E-08	1.038	3.33E-08
	470	4.41E-08	0.946	4.41E-08	0.994	4.41E-08	1.040	4.41E-08
	471	5.83E-08	0.948	5.83E-08	0.996	5.83E-08	1.042	5.83E-08
	472	7.68E-08	0.950	7.68E-08	0.998	7.68E-08	1.044	7.68E-08
	473	1.01E-07	0.952	1.01E-07	1.000	1.01E-07	1.046	1.01E-07
	474	1.32E-07	0.954	1.32E-07	1.002	1.32E-07	1.049	1.32E-07
	475	1.72E-07	0.956	1.72E-07	1.004	1.72E-07	1.051	1.72E-07
	476	2.24E-07	0.958	2.24E-07	1.006	2.24E-07	1.053	2.24E-07
	477	2.91E-07	0.960	2.91E-07	1.008	2.91E-07	1.055	2.91E-07
	478	3.76E-07	0.962	3.76E-07	1.011	3.76E-07	1.058	3.76E-07
	479	4.85E-07	0.964	4.85E-07	1.013	4.85E-07	1.060	4.85E-07
	480	6.23E-07	0.966	6.23E-07	1.015	6.23E-07	1.062	6.23E-07
	481	7.99E-07	0.968	7.99E-07	1.017	7.99E-07	1.064	7.99E-07
	482	1.02E-06	0.970	1.02E-06	1.019	1.02E-06	1.066	1.02E-06
	483	1.30E-06	0.972	1.30E-06	1.021	1.30E-06	1.069	1.30E-06
	484	1.66E-06	0.974	1.66E-06	1.023	1.66E-06	1.071	1.66E-06
	485	2.10E-06	0.976	2.10E-06	1.025	2.10E-06	1.073	2.10E-06
	486	2.65E-06	0.978	2.65E-06	1.027	2.65E-06	1.075	2.65E-06

487	3.34E-06	0.980	3.34E-06	1.030	3.34E-06	1.077	3.34E-06
488	4.20E-06	0.982	4.20E-06	1.032	4.20E-06	1.080	4.20E-06
489	5.27E-06	0.984	5.27E-06	1.034	5.27E-06	1.082	5.27E-06
490	6.59E-06	0.986	6.59E-06	1.036	6.59E-06	1.084	6.59E-06
491	8.21E-06	0.988	8.21E-06	1.038	8.21E-06	1.086	8.21E-06
492	1.02E-05	0.990	1.02E-05	1.040	1.02E-05	1.088	1.02E-05
493	1.27E-05	0.992	1.27E-05	1.042	1.27E-05	1.091	1.27E-05
494	1.57E-05	0.994	1.57E-05	1.044	1.57E-05	1.093	1.57E-05
495	1.93E-05	0.996	1.93E-05	1.047	1.93E-05	1.095	1.93E-05
496	2.38E-05	0.998	2.38E-05	1.049	2.38E-05	1.097	2.38E-05
497	2.92E-05	1.000	2.92E-05	1.051	2.92E-05	1.100	2.92E-05
498	3.57E-05	1.002	3.57E-05	1.053	3.57E-05	1.102	3.57E-05
499	4.36E-05	1.004	4.36E-05	1.055	4.36E-05	1.104	4.36E-05
500	5.31E-05	1.006	5.31E-05	1.057	5.31E-05	1.106	5.31E-05
501	6.44E-05	1.008	6.44E-05	1.059	6.44E-05	1.108	6.44E-05
502	7.81E-05	1.010	7.81E-05	1.061	7.81E-05	1.111	7.81E-05
503	9.43E-05	1.012	9.43E-05	1.063	9.43E-05	1.113	9.43E-05
504	1.14E-04	1.014	1.14E-04	1.066	1.14E-04	1.115	1.14E-04
505	1.37E-04	1.016	1.37E-04	1.068	1.37E-04	1.117	1.37E-04
506	1.64E-04	1.018	1.64E-04	1.070	1.64E-04	1.119	1.64E-04
507	1.96E-04	1.020	1.96E-04	1.072	1.96E-04	1.122	1.96E-04
508	2.34E-04	1.022	2.34E-04	1.074	2.34E-04	1.124	2.34E-04
509	2.79E-04	1.024	2.79E-04	1.076	2.79E-04	1.126	2.79E-04
510	3.31E-04	1.026	3.31E-04	1.078	3.31E-04	1.128	3.31E-04
511	3.92E-04	1.028	3.92E-04	1.080	3.92E-04	1.131	3.92E-04
512	4.64E-04	1.030	4.64E-04	1.082	4.64E-04	1.133	4.64E-04
513	5.47E-04	1.032	5.47E-04	1.085	5.47E-04	1.135	5.47E-04
514	6.44E-04	1.034	6.44E-04	1.087	6.44E-04	1.137	6.44E-04
515	7.56E-04	1.036	7.56E-04	1.089	7.56E-04	1.139	7.56E-04
516	8.85E-04	1.038	8.85E-04	1.091	8.85E-04	1.142	8.85E-04
517	1.03E-03	1.040	1.03E-03	1.093	1.03E-03	1.144	1.03E-03
518	1.21E-03	1.042	1.21E-03	1.095	1.21E-03	1.146	1.21E-03
519	1.40E-03	1.044	1.40E-03	1.097	1.40E-03	1.148	1.40E-03
520	1.63E-03	1.046	1.63E-03	1.099	1.63E-03	1.150	1.63E-03
521	1.89E-03	1.048	1.89E-03	1.101	1.89E-03	1.153	1.89E-03
522	2.18E-03	1.050	2.18E-03	1.104	2.18E-03	1.155	2.18E-03
523	2.51E-03	1.052	2.51E-03	1.106	2.51E-03	1.157	2.51E-03
524	2.89E-03	1.054	2.89E-03	1.108	2.89E-03	1.159	2.89E-03
525	3.32E-03	1.056	3.32E-03	1.110	3.32E-03	1.162	3.32E-03
526	3.80E-03	1.058	3.80E-03	1.112	3.80E-03	1.164	3.80E-03
527	4.35E-03	1.060	4.35E-03	1.114	4.35E-03	1.166	4.35E-03
528	4.96E-03	1.062	4.96E-03	1.116	4.96E-03	1.168	4.96E-03
529	5.64E-03	1.064	5.64E-03	1.118	5.64E-03	1.170	5.64E-03
530	6.41E-03	1.066	6.41E-03	1.121	6.41E-03	1.173	6.41E-03
531	7.26E-03	1.068	7.26E-03	1.123	7.26E-03	1.175	7.26E-03
532	8.22E-03	1.070	8.22E-03	1.125	8.22E-03	1.177	8.22E-03
533	9.28E-03	1.072	9.28E-03	1.127	9.28E-03	1.179	9.28E-03
534	1.04E-02	1.074	1.04E-02	1.129	1.04E-02	1.181	1.04E-02
535	1.17E-02	1.076	1.17E-02	1.131	1.17E-02	1.184	1.17E-02
536	1.32E-02	1.078	1.32E-02	1.133	1.32E-02	1.186	1.32E-02
537	1.48E-02	1.080	1.48E-02	1.135	1.48E-02	1.188	1.48E-02
538	1.65E-02	1.082	1.65E-02	1.137	1.65E-02	1.190	1.65E-02

539	1.84E-02	1.085	1.84E-02	1.140	1.84E-02	1.192	1.84E-02
540	2.05E-02	1.087	2.05E-02	1.142	2.05E-02	1.195	2.05E-02
541	2.28E-02	1.089	2.28E-02	1.144	2.28E-02	1.197	2.28E-02
542	2.52E-02	1.091	2.52E-02	1.146	2.52E-02	1.199	2.52E-02
543	2.79E-02	1.093	2.79E-02	1.148	2.79E-02	1.201	2.79E-02
544	3.09E-02	1.095	3.09E-02	1.150	3.09E-02	1.204	3.09E-02
545	3.41E-02	1.097	3.41E-02	1.152	3.41E-02	1.206	3.41E-02
546	3.75E-02	1.099	3.75E-02	1.154	3.75E-02	1.208	3.75E-02
547	4.12E-02	1.101	4.12E-02	1.156	4.12E-02	1.210	4.12E-02
548	4.52E-02	1.103	4.52E-02	1.159	4.52E-02	1.212	4.52E-02
549	4.95E-02	1.105	4.95E-02	1.161	4.95E-02	1.215	4.95E-02
550	5.40E-02	1.107	5.40E-02	1.163	5.40E-02	1.217	5.40E-02
551	5.90E-02	1.109	5.90E-02	1.165	5.90E-02	1.219	5.90E-02
552	6.42E-02	1.111	6.42E-02	1.167	6.42E-02	1.221	6.42E-02
553	6.98E-02	1.113	6.98E-02	1.169	6.98E-02	1.223	6.98E-02
554	7.57E-02	1.115	7.57E-02	1.171	7.57E-02	1.226	7.57E-02
555	8.21E-02	1.117	8.21E-02	1.173	8.21E-02	1.228	8.21E-02
556	8.87E-02	1.119	8.87E-02	1.175	8.87E-02	1.230	8.87E-02
557	9.58E-02	1.121	9.58E-02	1.178	9.58E-02	1.232	9.58E-02
558	1.03E-01	1.123	1.03E-01	1.180	1.03E-01	1.235	1.03E-01
559	1.11E-01	1.125	1.11E-01	1.182	1.11E-01	1.237	1.11E-01
560	1.19E-01	1.127	1.19E-01	1.184	1.19E-01	1.239	1.19E-01
561	1.28E-01	1.129	1.28E-01	1.186	1.28E-01	1.241	1.28E-01
562	1.37E-01	1.131	1.37E-01	1.188	1.37E-01	1.243	1.37E-01
563	1.47E-01	1.133	1.47E-01	1.190	1.47E-01	1.246	1.47E-01
564	1.57E-01	1.135	1.57E-01	1.192	1.57E-01	1.248	1.57E-01
565	1.67E-01	1.137	1.67E-01	1.195	1.67E-01	1.250	1.67E-01
566	1.78E-01	1.139	1.78E-01	1.197	1.78E-01	1.252	1.78E-01
567	1.89E-01	1.141	1.89E-01	1.199	1.89E-01	1.254	1.89E-01
568	2.00E-01	1.143	2.00E-01	1.201	2.00E-01	1.257	2.00E-01
569	2.12E-01	1.145	2.12E-01	1.203	2.12E-01	1.259	2.12E-01
570	2.25E-01	1.147	2.25E-01	1.205	2.25E-01	1.261	2.25E-01
571	2.37E-01	1.149	2.37E-01	1.207	2.37E-01	1.263	2.37E-01
572	2.50E-01	1.151	2.50E-01	1.209	2.50E-01	1.265	2.50E-01
573	2.64E-01	1.153	2.64E-01	1.211	2.64E-01	1.268	2.64E-01
574	2.78E-01	1.155	2.78E-01	1.214	2.78E-01	1.270	2.78E-01
575	2.92E-01	1.157	2.92E-01	1.216	2.92E-01	1.272	2.92E-01
576	3.06E-01	1.159	3.06E-01	1.218	3.06E-01	1.274	3.06E-01
577	3.21E-01	1.161	3.21E-01	1.220	3.21E-01	1.277	3.21E-01
578	3.36E-01	1.163	3.36E-01	1.222	3.36E-01	1.279	3.36E-01
579	3.51E-01	1.165	3.51E-01	1.224	3.51E-01	1.281	3.51E-01
580	3.66E-01	1.167	3.66E-01	1.226	3.66E-01	1.283	3.66E-01
581	3.82E-01	1.169	3.82E-01	1.228	3.82E-01	1.285	3.82E-01
582	3.97E-01	1.171	3.97E-01	1.230	3.97E-01	1.288	3.97E-01
583	4.13E-01	1.173	4.13E-01	1.233	4.13E-01	1.290	4.13E-01
584	4.29E-01	1.175	4.29E-01	1.235	4.29E-01	1.292	4.29E-01
585	4.45E-01	1.177	4.45E-01	1.237	4.45E-01	1.294	4.45E-01
586	4.61E-01	1.179	4.61E-01	1.239	4.61E-01	1.296	4.61E-01
587	4.77E-01	1.181	4.77E-01	1.241	4.77E-01	1.299	4.77E-01
588	4.94E-01	1.183	4.94E-01	1.243	4.94E-01	1.301	4.94E-01
589	5.10E-01	1.185	5.10E-01	1.245	5.10E-01	1.303	5.10E-01
590	5.26E-01	1.187	5.26E-01	1.247	5.26E-01	1.305	5.26E-01

591	5.42E-01	1.189	5.42E-01	1.249	5.42E-01	1.308	5.42E-01
592	5.58E-01	1.191	5.58E-01	1.252	5.58E-01	1.310	5.58E-01
593	5.74E-01	1.193	5.74E-01	1.254	5.74E-01	1.312	5.74E-01
594	5.89E-01	1.195	5.89E-01	1.256	5.89E-01	1.314	5.89E-01
595	6.05E-01	1.197	6.05E-01	1.258	6.05E-01	1.316	6.05E-01
596	6.20E-01	1.199	6.20E-01	1.260	6.20E-01	1.319	6.20E-01
597	6.35E-01	1.201	6.35E-01	1.262	6.35E-01	1.321	6.35E-01
598	6.50E-01	1.203	6.50E-01	1.264	6.50E-01	1.323	6.50E-01
599	6.65E-01	1.205	6.65E-01	1.266	6.65E-01	1.325	6.65E-01
600	6.79E-01	1.207	6.79E-01	1.268	6.79E-01	1.327	6.79E-01
601	6.93E-01	1.209	6.93E-01	1.271	6.93E-01	1.330	6.93E-01
602	7.07E-01	1.211	7.07E-01	1.273	7.07E-01	1.332	7.07E-01
603	7.20E-01	1.213	7.20E-01	1.275	7.20E-01	1.334	7.20E-01
604	7.33E-01	1.215	7.33E-01	1.277	7.33E-01	1.336	7.33E-01
605	7.46E-01	1.217	7.46E-01	1.279	7.46E-01	1.338	7.46E-01
606	7.59E-01	1.219	7.59E-01	1.281	7.59E-01	1.341	7.59E-01
607	7.71E-01	1.221	7.71E-01	1.283	7.71E-01	1.343	7.71E-01
608	7.82E-01	1.223	7.82E-01	1.285	7.82E-01	1.345	7.82E-01
609	7.94E-01	1.225	7.94E-01	1.288	7.94E-01	1.347	7.94E-01
610	8.05E-01	1.227	8.05E-01	1.290	8.05E-01	1.350	8.05E-01
611	8.15E-01	1.229	8.15E-01	1.292	8.15E-01	1.352	8.15E-01
612	8.25E-01	1.231	8.25E-01	1.294	8.25E-01	1.354	8.25E-01
613	8.35E-01	1.233	8.35E-01	1.296	8.35E-01	1.356	8.35E-01
614	8.45E-01	1.235	8.45E-01	1.298	8.45E-01	1.358	8.45E-01
615	8.54E-01	1.237	8.54E-01	1.300	8.54E-01	1.361	8.54E-01
616	8.62E-01	1.239	8.62E-01	1.302	8.62E-01	1.363	8.62E-01
617	8.71E-01	1.241	8.71E-01	1.304	8.71E-01	1.365	8.71E-01
618	8.79E-01	1.243	8.79E-01	1.307	8.79E-01	1.367	8.79E-01
619	8.86E-01	1.245	8.86E-01	1.309	8.86E-01	1.369	8.86E-01
620	8.94E-01	1.247	8.94E-01	1.311	8.94E-01	1.372	8.94E-01
621	9.00E-01	1.249	9.00E-01	1.313	9.00E-01	1.374	9.00E-01
622	9.07E-01	1.252	9.07E-01	1.315	9.07E-01	1.376	9.07E-01
623	9.13E-01	1.254	9.13E-01	1.317	9.13E-01	1.378	9.13E-01
624	9.19E-01	1.256	9.19E-01	1.319	9.19E-01	1.381	9.19E-01
625	9.25E-01	1.258	9.25E-01	1.321	9.25E-01	1.383	9.25E-01
626	9.30E-01	1.260	9.30E-01	1.323	9.30E-01	1.385	9.30E-01
627	9.35E-01	1.262	9.35E-01	1.326	9.35E-01	1.387	9.35E-01
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629	9.44E-01	1.266	9.44E-01	1.330	9.44E-01	1.392	9.44E-01
630	9.48E-01	1.268	9.48E-01	1.332	9.48E-01	1.394	9.48E-01
631	9.52E-01	1.270	9.52E-01	1.334	9.52E-01	1.396	9.52E-01
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633	9.59E-01	1.274	9.59E-01	1.338	9.59E-01	1.400	9.59E-01
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638	9.73E-01	1.284	9.73E-01	1.349	9.73E-01	1.412	9.73E-01
639	9.75E-01	1.286	9.75E-01	1.351	9.75E-01	1.414	9.75E-01
640	9.77E-01	1.288	9.77E-01	1.353	9.77E-01	1.416	9.77E-01
641	9.79E-01	1.290	9.79E-01	1.355	9.79E-01	1.418	9.79E-01
642	9.81E-01	1.292	9.81E-01	1.357	9.81E-01	1.420	9.81E-01

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645	9.86E-01	1.298	9.86E-01	1.364	9.86E-01	1.427	9.86E-01
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648	9.89E-01	1.304	9.89E-01	1.370	9.89E-01	1.434	9.89E-01
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661	9.97E-01	1.330	9.97E-01	1.397	9.97E-01	1.462	9.97E-01
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665	9.98E-01	1.338	9.98E-01	1.406	9.98E-01	1.471	9.98E-01
666	9.98E-01	1.340	9.98E-01	1.408	9.98E-01	1.473	9.98E-01
667	9.99E-01	1.342	9.99E-01	1.410	9.99E-01	1.476	9.99E-01
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671	9.99E-01	1.350	9.99E-01	1.419	9.99E-01	1.485	9.99E-01
672	9.99E-01	1.352	9.99E-01	1.421	9.99E-01	1.487	9.99E-01
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674	9.99E-01	1.356	9.99E-01	1.425	9.99E-01	1.491	9.99E-01
675	9.99E-01	1.358	9.99E-01	1.427	9.99E-01	1.493	9.99E-01
676	1.00E+00	1.360	1.00E+00	1.429	1.00E+00	1.496	1.00E+00
677	1.00E+00	1.362	1.00E+00	1.431	1.00E+00	1.498	1.00E+00
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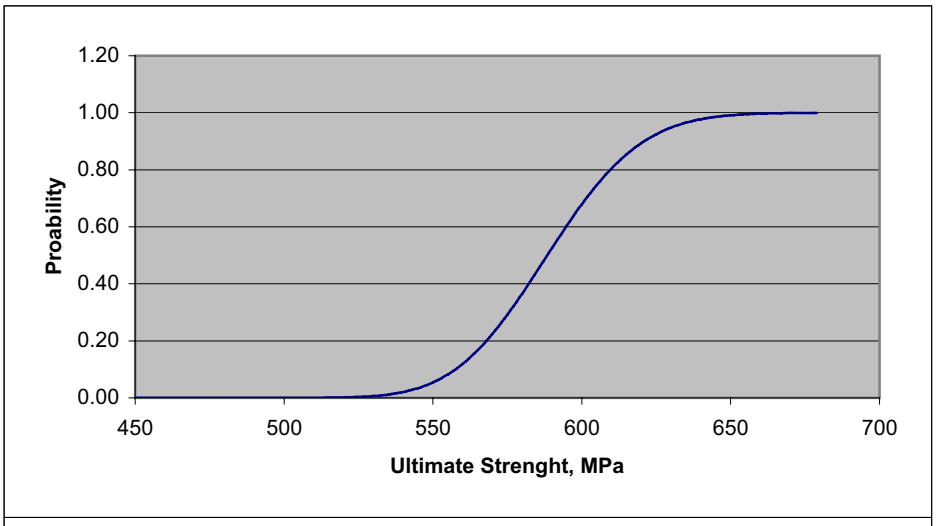
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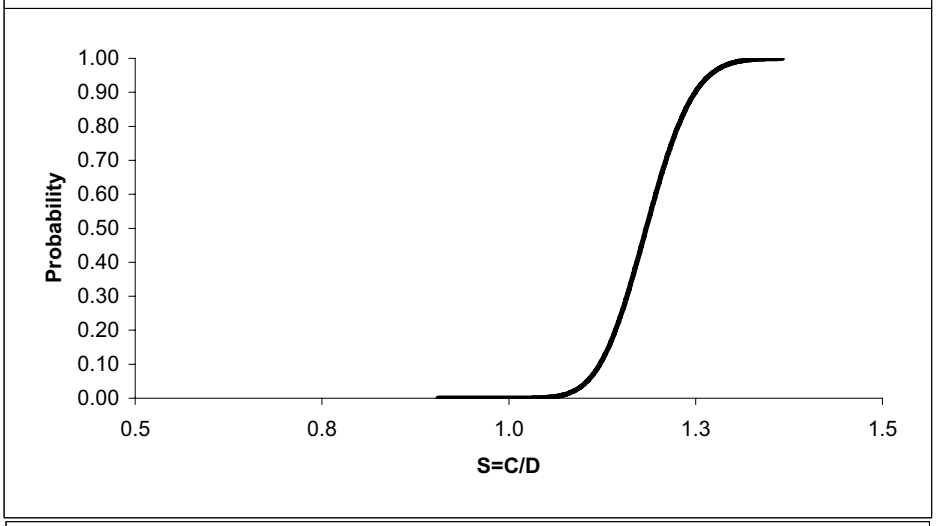
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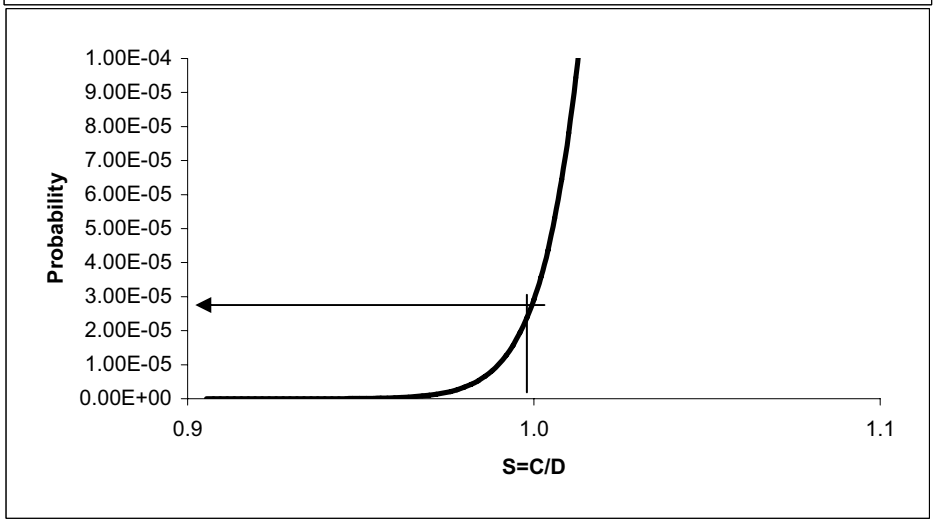
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