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Wall Thinning Criteria for Low Temperature - Low Pressure Piping (U) Task 91-030-1

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EXECUTIVE SUMMARY

This document contains analysis criteria to determine if corroded low temperature, low pressure piping can be safely accepted for continued service. The design of a large portion of the low temperature, low pressure piping at SRS is dominated by axial stresses. Recent UT thickness inspections of SRS piping have indicated locally thinned areas (LTA) in some pipes. The existing wall thinning criteria, WSRC-TR-92-236, contains local thinning criteria adopted from ASME Code Case N-480. The N-480 criteria were developed for high pressure piping where hoop stress dominates the design. Use of the N-480 criteria for low pressure piping is both awkward and overly conservative. Thus, LTA criteria is developed in this document for use on SRS low temperature, low pressure piping.

Several minor refinements to the existing criteria, WSRC-TR-92-236, based on recent experience, are also made.

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1. Introduction and Scope

This acceptance criteria is intended to prevent gross rupture or rapidly propagating failure during normal and abnormal operating conditions. Pitting may be present in the carbon steel piping. While the acceptance criteria have provisions to preclude gross rupture through a pitted region, they do not protect against throughwall pit growth and subsequent leakage. Potential leakage through a pit in low pressure piping is less than the post-DBE design basis leakage. Both the uniform thinning and LTA criteria protect against leakage, since their potential for leakage is larger.

The acceptance criteria protects against gross rupture due to general wall thinning, local wall thinning (LTA's), pitting, and fracture through weld defects. General wall thinning calculations are based on the restart criteria, SEP-24. LTA criteria for hoop stresses are based on ASME Code Case N-480 "Examination Requirements for Pipe Wall Thinning Due to Single Phase Erosion and Corrosion". The LTA criteria for axial stress is based on an effective average thickness concept, which prevents plastic collapse of a locally thinned pipe. Limits on pit density, based on an effective cross section concept, are used to prevent gross rupture through a group of pits. The CEGB R-6 failure assessment diagram is used in the fracture evaluation, along with postulated weld defects.

This criteria is intended for low temperature, low pressure piping systems. Corrosion and/or weld defects increase the peak stresses during normal operation and may lead to a reduction in fatigue life. Piping systems subject to significant thermal or mechanical fatigue will require additional analysis which is beyond the scope of this document.

2. Wall Thinning Criteria

Piping must meet any one of the three corrosion criteria:

(1) Uniform Thinning Criteria in Section 3.2

(2) Local Thinned Area Criteria in Section 3.3

(3) Pitting Criteria Section in 3.4

Piping not meeting this criteria may be accepted by further analysis or shall be repaired or replaced.

Worksheets to assist the analysts in implementing these criteria are given in Appendix C.

2.1. Definitions

$t_{min\ meas}$ is the minimum measured wall thickness.

$t_{average\ meas}$ is the average measured thickness.

$t_{req\ uniform\ hoop}$ is the code-of-record required uniform wall thickness for pressure design.

$t_{req\ uniform\ axial}$ is the required uniform wall thickness, defined in WSRC-TR-92-236. $t_{req\ uniform\ axial}$ is the minimum uniform thickness that meets (1) the code-of-record allowable axial stress; (2) fracture criteria for design weld defects; and (3) stability criteria to preclude compressive wrinkling.

$t_{req\ non\text{-}uniform\ axial}$ is the average wall thickness for non-uniform wall thinning that meets (1) the code-of-record allowable axial stress; (2) fracture criteria for design weld defects; and (3) stability criteria to preclude compressive wrinkling. The cross sectional area, section modulus and location of the neutral axis, shall be based on the measured non-uniform thinned geometry.

$F_{freq\ amp}$ is a frequency dependent, force magnification factor that reflects the increase in piping force due to a shift in the natural frequency. When

$$\beta = \frac{\text{length of thinner portion}}{\text{span length}} \leq \begin{cases} \dfrac{0.1}{1-\alpha} & \text{when } \alpha < 0.8 \\ 1.0 & \text{when } \alpha \geq 0.8 \end{cases}$$

$$\text{Where } \alpha = \frac{\text{average measured thickness (over 360°)}}{\text{design thickness}}$$

then $F_{freq\ amp} = 1$. Otherwise, for K-reactor piping on the -20' level, $F_{freq\ amp}$ is conservatively given in Figure 1B.

R_{LTA} is section modulus of a pipe with locally thinned areas divided by the section modulus based on the average thickness, t_{ave}. A conservative estimate of R_{LTA} is given in Figure 2.

$L_{t<t_{ave}}$ is the length of a region with a thickness less than $t_{average\ meas}$.

R_{pit} is the reduction in cross sectional area due to pitting. $R_{pit} = \left(1 - \sqrt{\frac{4\rho}{\pi}}\right)$ where $\rho = \frac{\text{Total Surface Area of Pits}}{\text{Surface Area of Pipe}}$. Where the pit density, ρ, can be determined by direct measurement of pitted piping, or by conservatively estimating the average pit radius, and counting the number of pits in a sample area, $\rho = \pi\, r_{pit}^2 \times \frac{\text{Number of pits}}{\text{Sample Area}}$.

$t_{base\ meas}$ is the measured thickness excluding pits, as shown in Figure 3.

2.2. Uniform Thinning Criteria

A thinned section is acceptable under the uniform thinning criteria if it meets either one of the following two criterion.

A) $t_{min\ meas} \geq 87.5\%\ t_{nominal}$

B) (1) $t_{min\ meas} \geq t_{req\ uniform\ hoop}$
(2) $t_{min\ meas} \geq t_{req\ uniform\ axial} \times F_{freq\ amp}$

2.3. Local Thinning Criteria

A locally thinned section is acceptable if it meets both the hoop stress criteria and the axial stress criteria.

2.3.1. Hoop Stress Criteria

A thinned section meets the hoop stress criteria if any one of the three criteria below are met.

A) $t_{min\ meas} \geq t_{req\ uniform\ hoop}$;

B) ASME Code Case N-480 Case 1(modified)
$t_{min\ meas} \geq t_{aloc}$, where t_{aloc} is determined from Curve 1 of Figure 4B.

C) ASME Code Case N-480 Case 2

(1) $$\frac{t_{min\ meas}}{t_{req\ uniform\ hoop}} \geq \frac{1.5\sqrt{R\ t_{req\ uniform\ hoop}}}{L}\left[1 - \frac{t_{nominal}}{t_{req\ uniform\ hoop}}\right] + 1.0;\ \text{and}$$

(2) $$\frac{t_{min\ meas}}{t_{req\ uniform\ hoop}} \geq \frac{0.353\ L_m}{\sqrt{R\ t_{req\ uniform\ hoop}}};\ \text{and}$$

(3) $t_{nominal} > 1.13\ t_{req\ uniform\ hoop}$; and

(4) $L_m < 2.65 \sqrt{R\ t_{req\ uniform\ hoop}}$

Where $t_{nominal}$, L and L_m are defined in Figure 4A.

2.3.2. Axial Stress Criteria

A thinned section meets the axial stress criteria if any one, of the three criterion below are met.

A) $t_{min\ meas} \geq t_{req\ uniform\ axial} \times F_{freq\ amp}$

B) (1) $t_{average\ meas} \geq t_{req\ uniform\ axial} \times F_{freq\ amp} / R_{LTA}$; and

(2) $\dfrac{L_{t<t_{ave}}}{Diameter} \leq \dfrac{\pi}{2}$

C) $t_{average\ meas} \geq t_{req\ non\text{-}uniform\ axial} \times F_{freq\ amp}$

2.4. Pitting Criteria

A pitted section is acceptable if it meets both of the following criterion.

A) $t_{base\ meas} \geq t_{req\ uniform\ hoop} / R_{pit}$

B) $t_{base\ meas} \geq t_{req\ uniform\ axial} \times F_{freq\ amp} / R_{pit}$

3. COMMENTARY

Several minor refinements to the existing uniform wall thinning criteria [1], and a reformulation of the locally thinned area (LTA) criteria are discussed in this section. The pitting and fracture criteria remain unchanged from Reference 1 and are not discussed further.

3.1. Uniform Thinning Criteria

The uniform thinning criteria was developed in Reference 1. Recent wall thinning evaluations [3, 4] have shown that the moment redistribution wall thinning criteria[1] is less stringent than the natural frequency criteria[2]. Additionally, moment redistribution tends to reduce stresses in the thinned area. The moment redistribution criteria is no longer used.

Recent wall thinning evaluations [3, 4] have also shown that the natural frequency criteria,

$$\beta = \frac{\text{length of thinner portion}}{\text{span length}} \leq \begin{cases} \dfrac{0.1}{1-\alpha} & \text{when } \alpha < 0.8 \\ 1.0 & \text{when } \alpha \geq 0.8 \end{cases} \qquad (4.1)$$

$$\text{Where } \alpha = \frac{\text{average measured thickness (over 360°)}}{\text{design thickness}}$$

may be exceeded. This criteria was developed using the simple conservative model shown in Figure 1A to preclude a 10% shift in the natural frequency. The 10% allowable frequency shift is consistent with industry standard as-built piping tolerances [5], which have been accepted by the NRC.

Examination of the K-reactor -20' floor response spectrum indicated that a 10% decrease in natural frequency corresponded to a 10% increase in

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1 Developed in Section E.1 of Reference 1.

2 Developed in Section E.2 of Reference 1.

acceleration (and piping force) when the natural frequency was in the 3 to 7 Hertz range [1]. A frequency dependent force magnification factor, $F_{freq\ amp}$, reflects the increase in piping forces (bending moments) due to a shift in the natural frequency, is used when the frequency shift is greater than 10%. This factor is conservatively based on the simply supported beam model with wall thinning in its center [1], Figure 1A and the K-reactor -20' floor response spectra [13], as shown in Appendix A. This *evaluation using simple structural models* is consistent with the as built piping resolution process [5].

3.2. Local Thinning Criteria

Existing criteria for local wall thinning [2, 6, 7, and 8] are primarily based on pressure loading. Low pressure piping is dominated by axial stresses as opposed to high pressure piping which is dominated by hoop stress. For low pressure piping, the existing local wall thinning criteria are used to preclude hoop stress failure and subsequent leakage. Additional criteria, based on the moment capacity, are used to preclude axial stress failure. A pipe with LTAs is acceptable if it meets both the hoop stress criteria and the axial stress criteria.

3.2.1. Hoop Stress Criteria

The bases for the Code Case N-480 [2] criteria for local wall thinning are:

Case 1 Burst (internal pressure) test of degraded piping [6, 7, 8]. The burst test criteria were developed for pipelines and have neglected axial stresses. Axial stresses are indirectly accounted for in the Code Case by limiting the transverse amount of thinning to $\sqrt{Rt}$ [2].

Case 2 Branch reinforcement rules [6, 7]. The branch reinforcement rules require that the area lost due to thinning be compensated with material exceeding the minimum required thickness, distributed around the thinned area. Since the thinned area is replaced, both hoop and axial stress are accounted for.

Case 3 Local membrane stresses on an axisymmetric thinned region [6,7]. An axisymmetric section of pipe with local wall thinning subject to internal pressure was analyzed. The criteria are set up to limit the local membrane stresses resulting from internal pressure. A secondary check on a 360° thinned pipe is made to account for bending stresses.

In this document, the axial wall thinning criteria is treated separately from the hoop wall thinning criteria. Thus the limit on the transverse amount of thinning, $\sqrt{Rt}$, in Case 1 and the secondary bending check in Case 3 are omitted. Since the Case 3 criteria, shown as Curve 2 in Figure 4 are more conservative than the Case 1 criteria, shown as Curve 1 in Figure 4, the Case 3 criteria are omitted.

3.2.2. Axial Stress Criteria

Recent UT thickness examinations of K-reactor piping [9, 10] have shown that local thinning does not extend 360° around the pipe circumference as assumed by Case 3 of the N-480 criteria. However, the thinning may exceed the transverse width limitations given by Case 1 and Case 2 of the N-480 Criteria. An axial stress criteria for locally thinned piping is developed in this section for various amounts of transverse wall thinning.

3.2.2.1. Development of Local Thinning Criteria

Returning to first principals, the axial and bending stresses in a pipe[3] can be calculated from

$$\sigma_m + \sigma_b = \frac{\text{Pressure}\ \pi\ R^2}{A} + \frac{\text{Moment} + \text{Pressure}\ \pi\ R^2\ \overline{Y}}{Z} \qquad (4.2)$$

where σ_m is the membrane stress,
σ_b is the bending stress,
Pressure is the internal pressure,
Moment is the applied bending moment,

3 Neglecting stress intensification factors.

R is the mean pipe radius,
A is the cross sectional area of the thinned pipe,
$\overline{Y}$ is the distance from the centroid to the neutral axis, and
Z is the section modulus of the thinned pipe.

The section properties of a thinned pipe can be calculated from

$$A = \int dA = \int_0^{2\pi} R\, t(\theta)\, d\theta \tag{4.3}$$

$$A\overline{Y} = \int y\, dA = \int_0^{2\pi} R\, t(\theta)\, R \operatorname{Cos}\theta\, d\theta \tag{4.4}$$

$$\text{Inertia} = \int y^2\, dA\Big|_{\text{about NA}} = \int_0^{2\pi} R\, t(\theta)\, (R \operatorname{Cos}\theta)^2\, d\theta - A\,\overline{Y}^2 \tag{4.5}$$

$$Z = \frac{\text{Inertia}}{R + \left|\overline{Y}\right|} \tag{4.6}$$

where $t(\theta)$ is the angular variation in wall thickness. A parametric study is performed in Appendix B which varies the thickness as a sinusoidal function:

$$t(\theta) = t_{max}\left(1 - b\,\frac{1 + \operatorname{Cos}(c\,\theta)}{2}\right) \tag{4.7}$$

where $b = \frac{t_{max} - t_{min}}{t_{max}}$, and
c is the number of equal spaced locations around the circumference with a thickness below the average thickness.

Since the circumference of a pipe is πD, the length of a region with a thickness less than t_{ave} is

$$L_{t<t_{ave}} = \frac{\pi D}{2c} \tag{4.8}$$

The angular variation of thickness is shown in Figure 5 for several postulated cases of wall thinning.

The distance to the neutral axis, $\overline{Y}$, for values of c greater than 3 and b=0.5 is approximately 3% of the radius. While the distance to the neutral axis is approximately 17% of the radius for c equal to 1. Considering that this criteria is intended for low pressure piping and that the distance to the neutral axis is relatively short, then the term Pressure $\pi R^2 \overline{Y}$, in Equation 4.2, can be neglected.

The section modulus, Equation 4.6, can be rewritten in compact form as

$$Z = R_{LTA}\, \pi\, R^2\, t_{ave} \tag{4.9}$$

Where R_{LTA} is a reduction factor for locally thinned areas. Equations for R_{LTA}, developed in Attachment B, are difficult to use. Alternately, a conservative envelope of R_{LTA} is presented graphically in Figure 2. When c is less than 1, $t(\theta)$ is always less than t_{max}. Thus, c is restricted to values greater than 1, and $L_{t<t_{ave}}$ is limited to less than or equal to $\pi/2$ pipe diameters. Analyses with $L_{t<t_{ave}}$ greater than $\pi/2$ pipe diameters should be done on a special case-by-case basis using the actual measured cross sectional geometry.

By definition, the average thickness of the pipe is given by

$$t_{ave} = \frac{A}{2\, \pi\, R} \tag{4.10}$$

Thus, the piping axial stress equation can be rewritten as

$$\sigma_m + \sigma_b = \frac{\text{Pressure}\ \pi\, R^2}{2\, \pi\, R\, t_{ave}} + \frac{\text{Moment}}{R_{LTA}\, \pi\, R^2 t_{ave}} \tag{4.11}$$

or, since R_{LTA} is always less than 1, the axial stress equation may be conservatively rewritten as

$$\sigma_m + \sigma_b \approx \frac{\dfrac{\text{Pressure}\ \pi R^2}{2\pi R\, t_{ave}} + \dfrac{\text{Moment}}{\pi R^2 t_{ave}}}{R_{LTA}} \qquad (4.12)$$

In Reference 1, the methodology is developed to calculate the minimum required uniform thickness, $t_{req\ uniform\ axial}$, that meets (1) the code-of-record allowable axial stress; (2) fracture criteria for design weld defects; and (3) stability criteria to preclude compressive wrinkling. The effective average thickness, $R_{LTA}\ t_{ave\ meas}$, must be greater than or equal to minimum required uniform thickness, $t_{req\ uniform\ axial}$, to give stresses less than or equal to $\sigma_m + \sigma_b$

$$t_{req\ uniform\ axial} \leq R_{LTA}\ t_{ave\ meas} \qquad (4.13)$$

or

$$t_{ave\ meas} \geq \frac{t_{req\ uniform\ axial}}{R_{LTA}} \qquad (4.14)$$

Equation 4.14 is used in the LTA axial stress criteria.

3.2.2.2. Use of Automated UT Data

Automated UT data collection techniques such as P-Scan are capable of providing 3-D contours of the thinned area. These systems can give the average thickness, t_{ave}, the standard deviation of the thickness, $t_{std\ dev}$, a thickness histogram, in addition to the minimum thickness, $t_{min\ meas}$. The UT thickness data examined to date appear to have normally distributed thicknesses. Thus it is possible to use a statistical estimate of the maximum and minimum thicknesses rather than the raw data.

$$t_{min\ meas} = t_{ave} - 3\ t_{std\ dev} \qquad (4.15)$$

$$t_{max\ meas} = t_{ave} + 3\ t_{std\ dev} \qquad (4.16)$$

Using the average ± 3 standard deviations avoids skewing the analysis because of one or two very small deep LTA's. If t_{ave} - 3 $t_{std\ dev}$ is less than the minimum measured value, the use of the measured minimum and maximum thicknesses is acceptable.

If only four discrete UT measurements on a pipe cross section at 3, 6, 9 and 12 o'clock are available and only one of the four readings is below $t_{req\ uniform\ axial}$, then, the LTA criteria may be used with $t_{ave} = 0.25\ \Sigma\ t_{measured}$ and $L_{t<t_{ave}} = \pi/2$ Diameter.

3.2.2.3. Evaluation of Secondary Stresses

The preceding equations are based on beam theory, where the bending stress is equal to the moment divided by the section modulus. When the locally thinned areas have a finite axial length and may be staggered, additional secondary stresses will be developed. A prototypical finite element analysis of a 24" diameter pipe with 'egg crate' wall thinning, Figure 6, is made to determine if the stress concentrations near locally thinned areas have a significant reduction in the moment capacity.

The finite element model consist of a 180° section of a 24" OD pipe, 4.19" long. The maximum wall thickness of the pipe is 0.25" and the minimum wall thickness is 0.125". The thickness has a sinusoidal variation in both directions with a period of 2.09", similar to Figure 5. The length of a region less than the average thickness is 1.05". The model consist of 9,216 eight noded solid continuum elements (C3D8). Four elements are used through the thickness, and the elements are approximately 0.25" long in the plane of the shell. The model is restrained axially at one end and at the plane of symmetry, as shown in Figure 7. Axial displacements are imposed at the free end to generate the applied bending moment. Simplified, bilinear material properties, typical of carbon steel piping, were assumed in this analysis with σ_y=30 ksi, σ_u=40 ksi, E=29,000 ksi, ε_u=0.10 and ν=0.30. Geometric nonlinearities are not considered in this analysis. The finite element analysis was performed using the ABAQUS code [11].

The applied bending moment is calculated by summing a moment of the reaction forces at the nodes with imposed axial displacements about the pipe centroid. Curvature is calculated by dividing the imposed rotation by the axial length of the model. Figure 8 contains the nonlinear moment-curvature plot of the thinned pipe [12].

The first solution point on the curve corresponds to a curvature of 0.00008 inches^{-1}, an average axial strain of 0.1%, which is below the yield strain, ε_y=0.103%. The maximum equivalent plastic strain is 0.05%, indicating minor load redistribution around the LTA's.

The last solution point on the curve corresponds to a curvature of 0.0014 inches^{-1}, an average axial strain of 1.7% and a maximum equivalent plastic strain of 3.9%. The magnitude of the equivalent plastic strain is acceptable, indicating that this severely corroded pipe can sustain the fully plastic bending moment.

The yield and plastic moments are calculated below for an equivalent pipe with $t=t_{ave}$.

$$M_y = \sigma_y \, \pi \, t_{ave} \, R^2 = 30 \, \pi \frac{0.25+0.125}{2} (11.906)^2 = 2500 \text{ in-kips} \quad (4.17)$$

$$M_p = \sigma_y \; 4 \, t_{ave} \, R^2 = 30 \times 4 \frac{0.25+0.125}{2} (11.906)^2 = 3200 \text{ in-kips} \quad (4.18)$$

Since the length of a region thinner than t_{ave} ÷ pipe diameter 1.05/24=0.04, is small, R_{LTA} approaches 1, Figure 2, and is ignored for this case. For larger thinned areas, the elastic section modulus should be multiplied by R_{LTA}. The plastic section modulus should also be reduced to account for the angular variation in thickness. However, the plastic section modulus reduction factor has not been developed.

The moment curvature relationship is also calculated by imposing a curvature, ϕ, calculating the strain distribution, $\varepsilon(\theta)$, calculating the stress distribution, $\sigma(\theta)$, and numerically integrating,

$$\text{Moment} = \int \sigma(\theta)\, y(\theta)\, dA = \int_0^{2\pi} \sigma(\theta)\, t_{ave}\, R^2 \cos\theta \, d\theta \quad (4.19)$$

This beam theory moment-curvature diagram is also shown in Figure 8 and summarized in the table below. As shown in Figure 8, the FEM analysis is 'softer' than the beam theory solution immediately after yield. This is due to limited yielding in the thinned areas. As the curvature increase and the section becomes fully plastic, then both solutions converge to a common ultimate capacity.

Comparison of Solutions

	FEM Analysis	Equations 4.17 and 4.18	Equation 4.19
Thickness	'Egg Crate' wall thinning, Figure 6	t_{ave}	t_{ave}
Material Model	Bilinear	Elastic-Plastic	Bilinear
Yield Moment	≈2500 in-kip	2500 in-kips	≈2500 in-kip
Plastic Moment @ ϕ=0.0014 in^{-1}	3150 in-kip	3200 in-kip	3300 in-kip

This finite element analysis demonstrates that a severely thinned section of piping (t_{min}=50% t_{max}), with an exaggerated 'egg crate' thinning pattern, has a moment capacity comparable to an equivalent uniform pipe with the thickness t_{ave}. Additionally, the LTA's were shown to slightly 'soften' the post yielding nonlinear behavior.

4. References

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3. SRT-MTS-921221, *GQN67 - Wall Thinning Evaluation*, G.E. Mertz, P.S. Lam and G.C. Kao, November 1992.

4. SRT-MTS-921225, *Supporting Calculations for SRT-MTS-921221 GQN67 - Wall Thinning Evaluation*, G.E. Mertz, P.S. Lam and G.C. Kao, November 1992.

5. EPRI NP-5639, *Guidelines for Piping System Reconciliation (NCIG-05, Revision 1)*, May 1988.

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12. *Computer Output: wt,* 16:07 12/1/92
Computer Output: wt2b, 16:45 12/2/92
Computer Output: wt2d, 9:42 12/3/92

13. Seismic Evaluation Procedure, SEP 11, Rev. 1, Savannah River Site Reactor Facilities Seismic Response Spectra, November 1989.

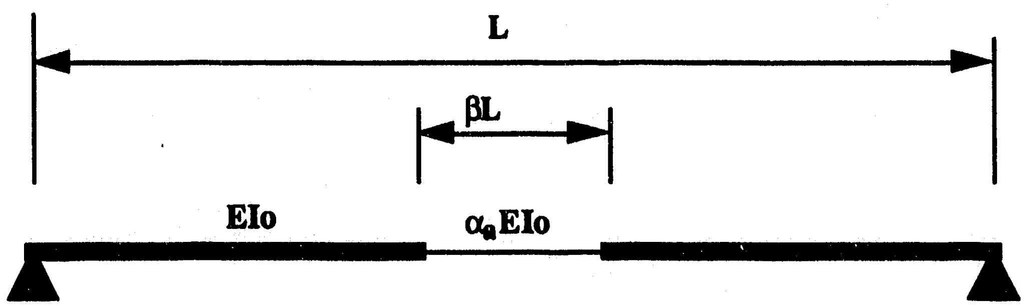


Figure 1A Simple Span Pipe Model

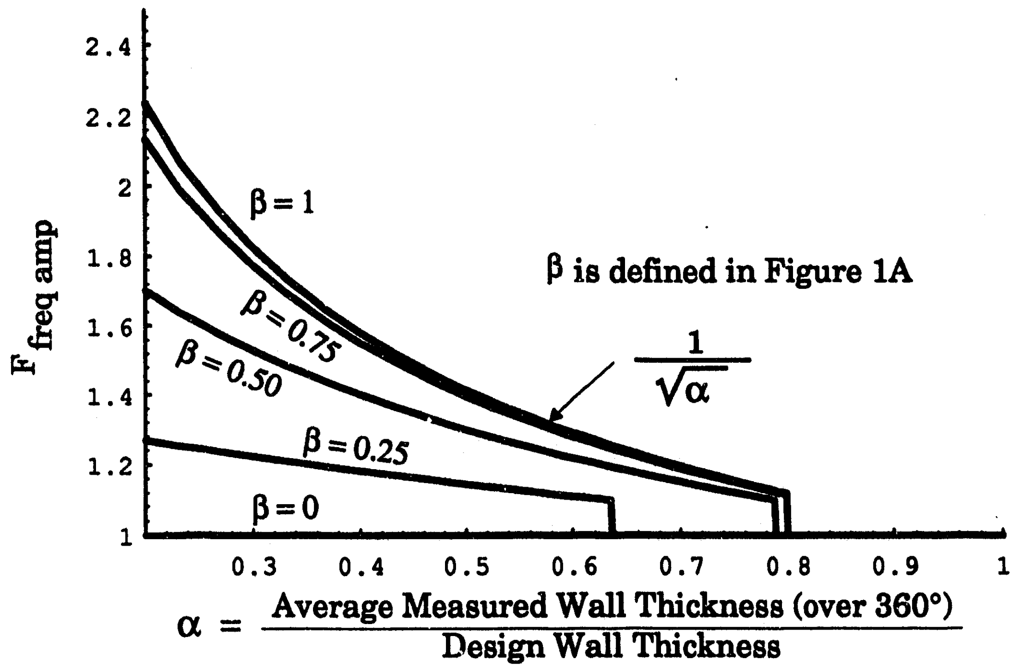


Figure 1B Frequency Dependent Force Magnification Factor, $F_{freq\ amp}$

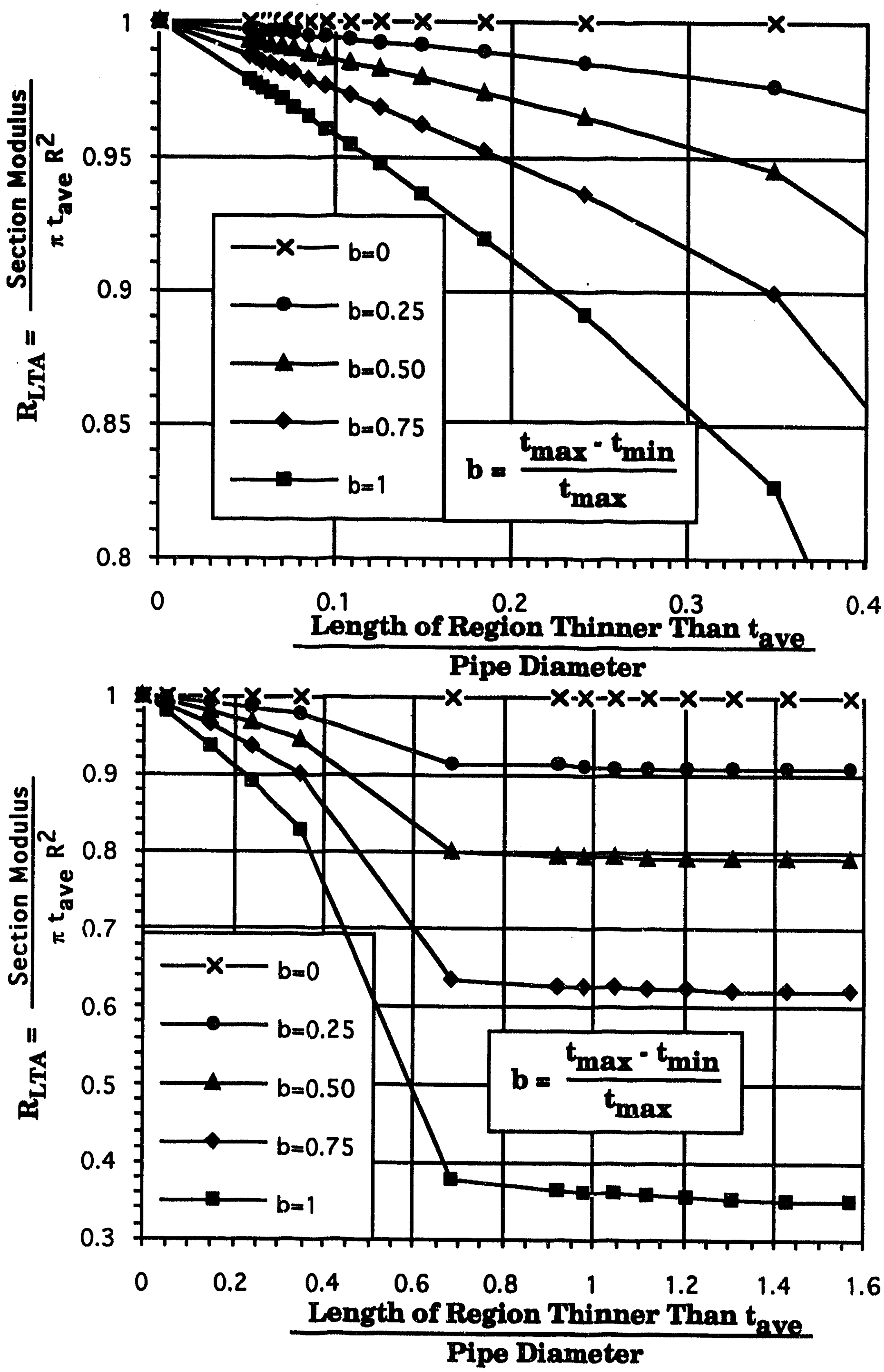


Figure 2 Ratio of Section Modulus to $\pi t_{ave} R^2$

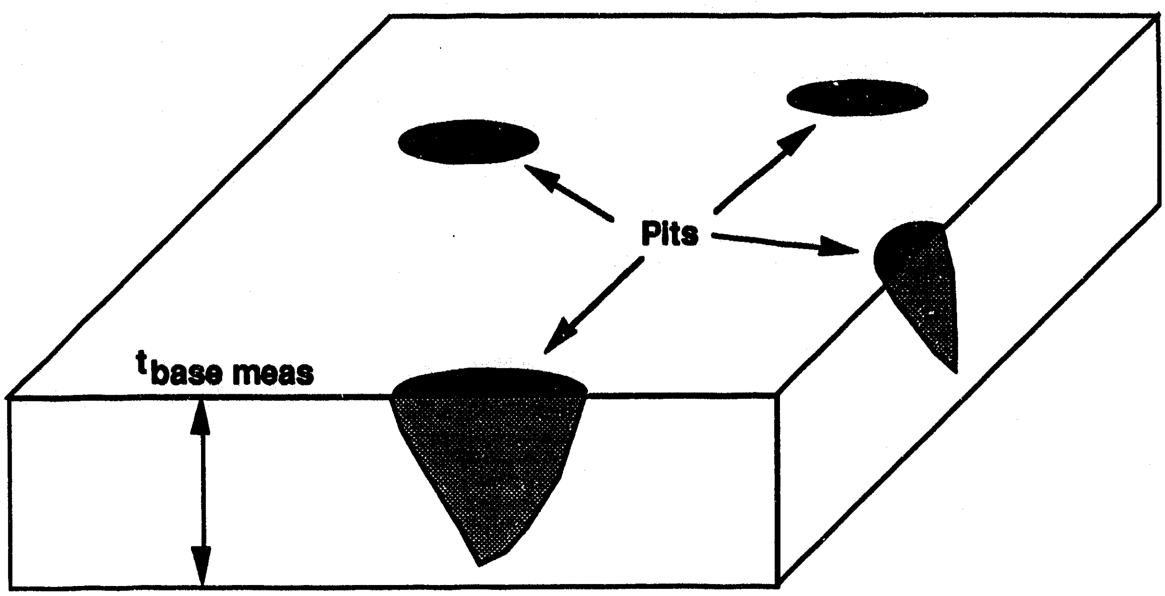


Figure 3 Average thickness, $t_{base\ meas}$

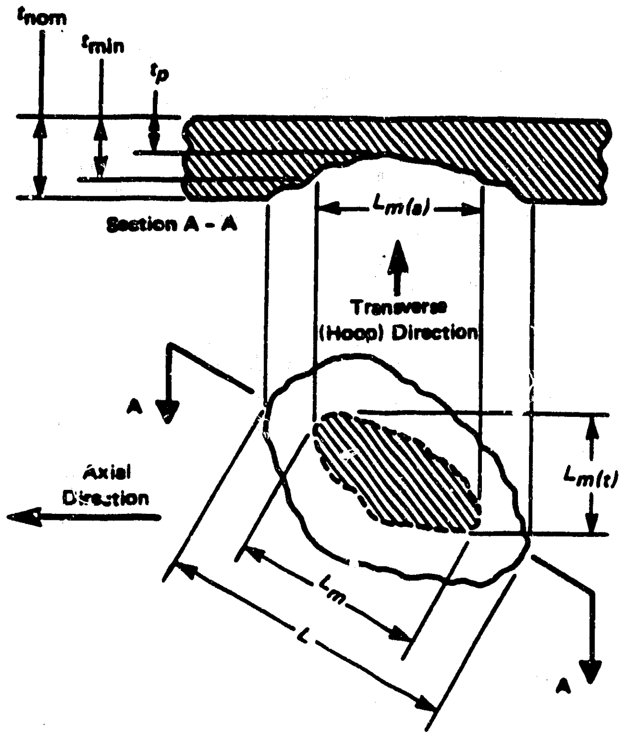


Figure 4A Illustration of Wall Thinning [2]

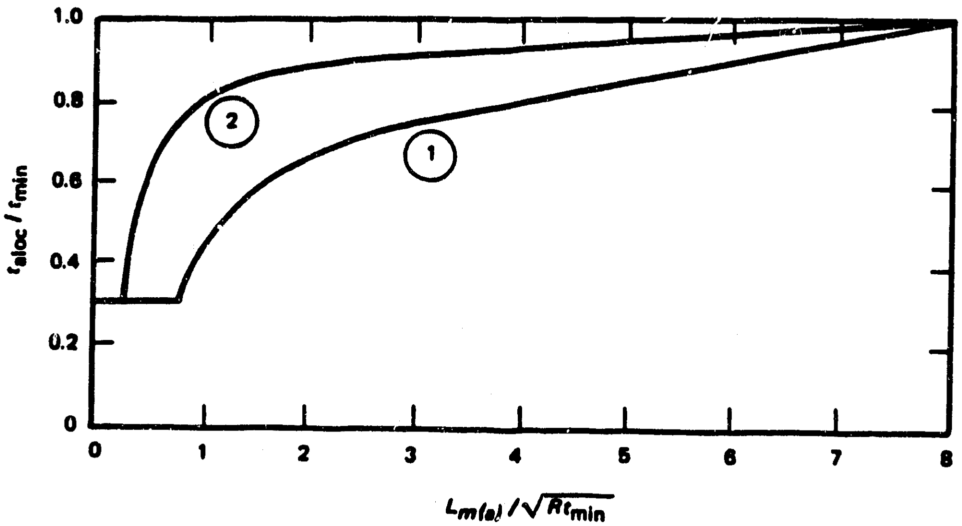


Figure 4B Allowable Depth and Length of Locally Thinned Areas [2]

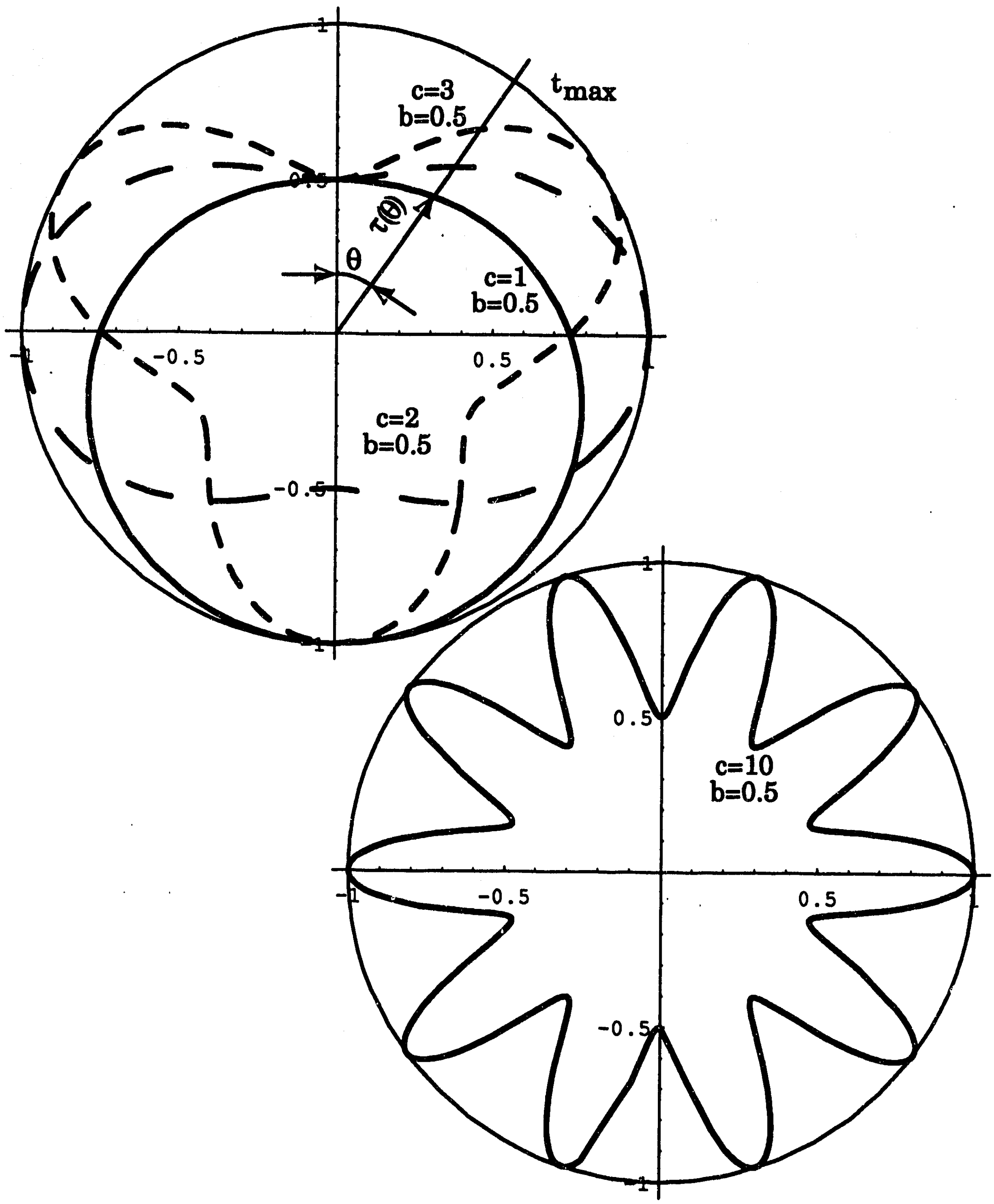


Figure 5 Postulated Angular Variation in Thickness

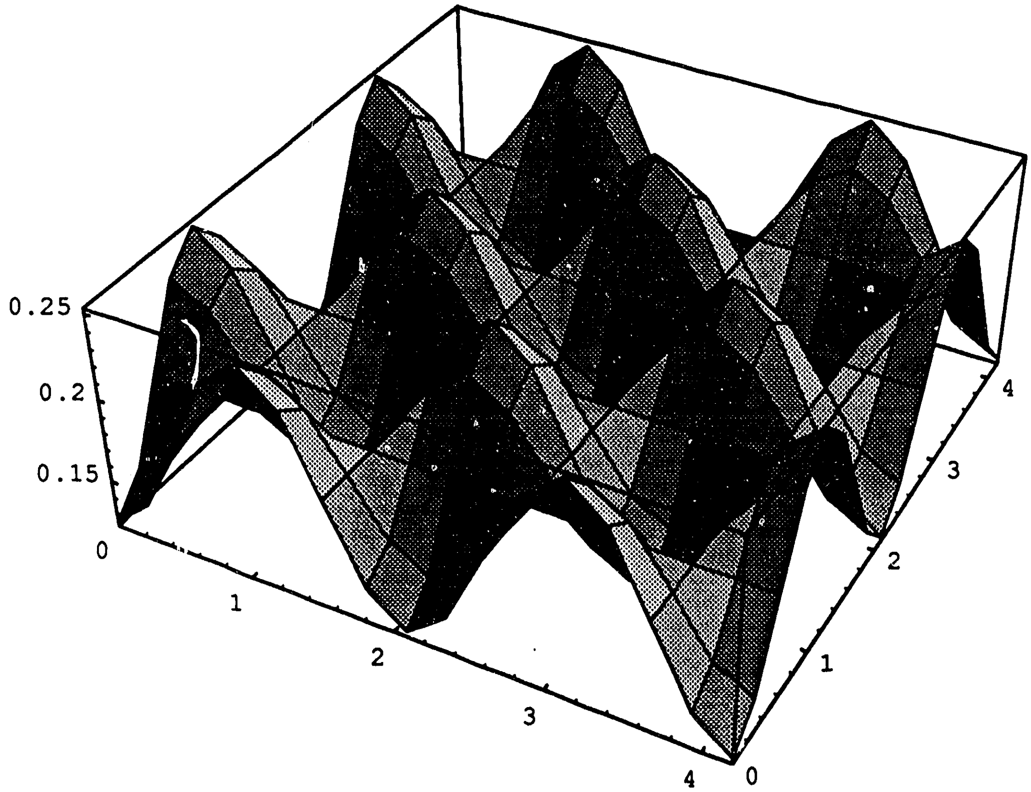


Figure 6 'Egg Crate' Wall Thinning Pattern

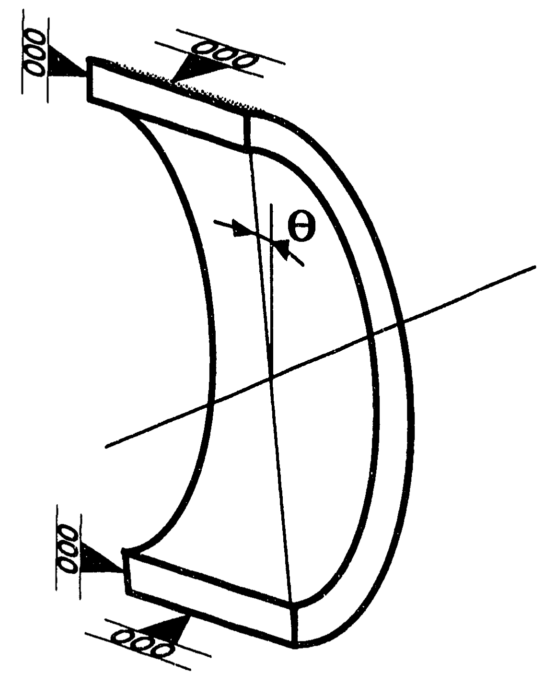


Figure 7 180° Pipe Model with Boundary Conditions

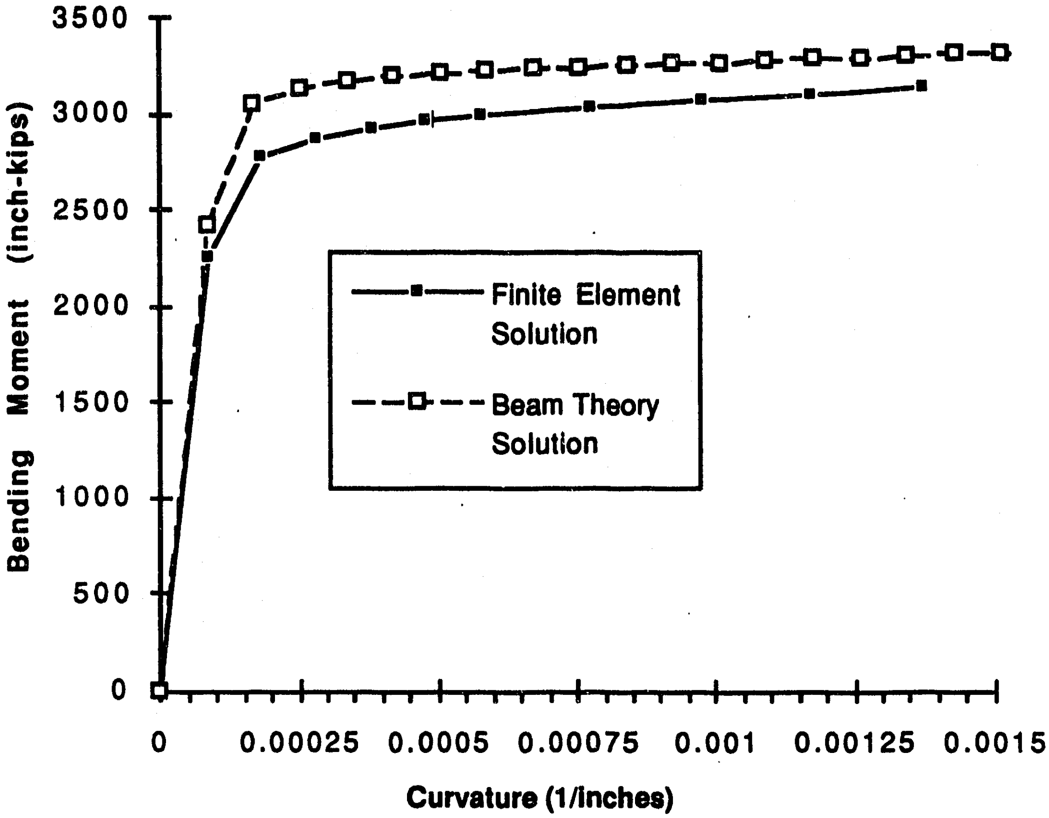


Figure 8 Moment Curvature Relationship for a 24" OD Pipe

$0.25"\ t_{max}, 0.125"\ t_{min}, L_{t<t_{ave}} = \frac{\pi D}{2 \times 36} = 1.05"$

$\sigma_y = 30ksi, E=29{,}000\ ksi, \sigma_u = 40ksi, \varepsilon_u=0.10$

Development of the Frequency Dependent Force Magnification Factor, F_{freq} amp

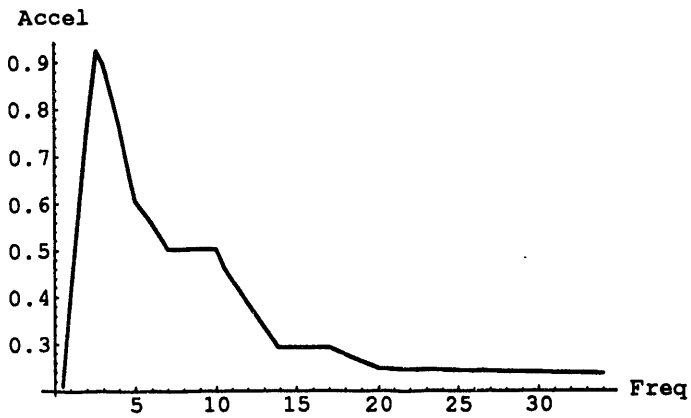
□ Determine the Increase in Acceleration Corresponding to a Decrease in Natural Frequency

Define the Floor Response Spectrum for the K reactor -20' level, 3% Dampening, From SEP-11, Revision 1... Freq is in Hertz, Accel's are in G's.

```
Freq={34,20,17,13.85,10.5,10,9,7.75,7,6,5,4,3,2.6,2,1,0.5};
KRM20TR03={0.237,0.248,0.293,0.293,0.462,0.502,0.502,0.502,
     0.502,0.558,0.606,0.767,0.898,0.925,0.749,0.394,0.21};
KRM20LO03={0.242,0.258,0.292,0.292,0.367,0.388,0.406,0.406,
     0.448,0.526,0.655,0.783,0.9,0.924,0.749,0.395,0.21};
```

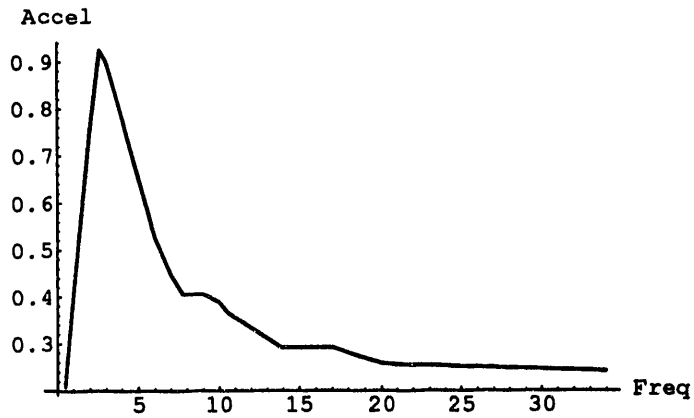
Plot the floor response spectra

```
Transverse=   ListPlot[Transpose[{Freq,KRM20TR03}],
              AxesLabel->{"Freq","Accel"},PlotJoined->True]
```



-Graphics-

```
Longitudinal=ListPlot[Transpose[{Freq,KRM20LO03}],
              AxesLabel->{"Freq","Accel"},PlotJoined->True]
```



-Graphics-

Number of data points used for spectra.

```
n=Length[Freq]
```

```
17
```

Define wr as the ratio of final to initial frequency.

Calculate the increase in response, Ffa, as the ratio of final to initial acceleration using both transverse and longitudinal accelerations.

```
wr={ };
final={ };
initial={ };
FfaTR={ };
FfaLO={ };
Do[
     Do[ Fj=Freq[[j]];
          Fi=Freq[[i]];
          wrij=N[ Fj/Fi   ,4];
          FfaTRij=N[ KRM20TR03[[j]]/KRM20TR03[[i]] ,4];
          FfaLOij=N[ KRM20LO03[[j]]/KRM20LO03[[i]] ,4];
          final=Append[ final,Fj ];
          initial=Append[initial,Fi ];
          wr=Append[wr,wrij ] ;
          FfaTR=Append[FfaTR,FfaTRij ];
          FfaLO=Append[FfaLO,FfaLOij ];
          (* Print[" i=",i," Freq i=",Fi,
                " j=",j," Freq j=",Fj,
                " wr=",wrij,
                " FfaTR=",FfaTRij," FfaLO=",FfaLOij] *)
          ,{j,i,n}]
     ,{i,1,n}]
```

Print Results

```
TableForm[Transpose[{final,initial,wr,FfaTR,FfaLO}],
     TableSpacing->{0,8},
     TableHeadings->{{},
     {"Final Freq","Inital Freq","WR","Ffa TR","Ffa LO"}}]
```

Final Freq	Inital Freq	WR	Ffa TR	Ffa LO
34	34	1.	1.	1.
20	34	0.5882	1.046	1.066
17	34	0.5	1.236	1.207
13.85	34	0.4074	1.236	1.207
10.5	34	0.3088	1.949	1.517
10	34	0.2941	2.118	1.603
9	34	0.2647	2.118	1.678
7.75	34	0.2279	2.118	1.678
7	34	0.2059	2.118	1.851
6	34	0.1765	2.354	2.174
5	34	0.1471	2.557	2.707
4	34	0.1176	3.236	3.236
3	34	0.08824	3.789	3.719
2.6	34	0.07647	3.903	3.818

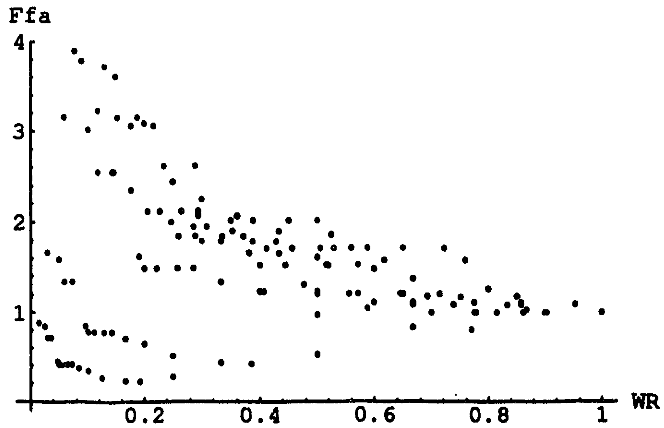
2	34	0.05882	3.16	3.095
1	34	0.02941	1.662	1.632
0.5	34	0.01471	0.8861	0.8678
20	20	1.	1.	1.
17	20	0.85	1.181	1.132
13.85	20	0.6925	1.181	1.132
10.5	20	0.525	1.863	1.422
10	20	0.5	2.024	1.504
9	20	0.45	2.024	1.574
7.75	20	0.3875	2.024	1.574
7	20	0.35	2.024	1.736
6	20	0.3	2.25	2.039
5	20	0.25	2.444	2.539
4	20	0.2	3.093	3.035
3	20	0.15	3.621	3.488
2.6	20	0.13	3.73	3.581
2	20	0.1	3.02	2.903
1	20	0.05	1.589	1.531
0.5	20	0.025	0.8468	0.814
17	17	1.	1.	1.
13.85	17	0.8147	1.	1.
10.5	17	0.6176	1.577	1.257
10	17	0.5882	1.713	1.329
9	17	0.5294	1.713	1.39
7.75	17	0.4559	1.713	1.39
7	17	0.4118	1.713	1.534
6	17	0.3529	1.904	1.801
5	17	0.2941	2.068	2.243
4	17	0.2353	2.618	2.682
3	17	0.1765	3.065	3.082
2.6	17	0.1529	3.157	3.164
2	17	0.1176	2.556	2.565
1	17	0.05882	1.345	1.353
0.5	17	0.02941	0.7167	0.7192
13.85	13.85	1.	1.	1.
10.5	13.85	0.7581	1.577	1.257
10	13.85	0.722	1.713	1.329
9	13.85	0.6498	1.713	1.39
7.75	13.85	0.5596	1.713	1.39
7	13.85	0.5054	1.713	1.534
6	13.85	0.4332	1.904	1.801
5	13.85	0.361	2.068	2.243
4	13.85	0.2888	2.618	2.682
3	13.85	0.2166	3.065	3.082
2.6	13.85	0.1877	3.157	3.164
2	13.85	0.1444	2.556	2.565
1	13.85	0.0722	1.345	1.353
0.5	13.85	0.0361	0.7167	0.7192
10.5	10.5	1.	1.	1.
10	10.5	0.9524	1.087	1.057
9	10.5	0.8571	1.087	1.106
7.75	10.5	0.7381	1.087	1.106
7	10.5	0.6667	1.087	1.221
6	10.5	0.5714	1.208	1.433
5	10.5	0.4762	1.312	1.785
4	10.5	0.381	1.66	2.134

3	10.5	0.2857	1.944	2.452
2.6	10.5	0.2476	2.002	2.518
2	10.5	0.1905	1.621	2.041
1	10.5	0.09524	0.8528	1.076
0.5	10.5	0.04762	0.4545	0.5722
10	10	1.	1.	1.
9	10	0.9	1.	1.046
7.75	10	0.775	1.	1.046
7	10	0.7	1.	1.155
6	10	0.6	1.112	1.356
5	10	0.5	1.207	1.688
4	10	0.4	1.528	2.018
3	10	0.3	1.789	2.32
2.6	10	0.26	1.843	2.381
2	10	0.2	1.492	1.93
1	10	0.1	0.7849	1.018
0.5	10	0.05	0.4183	0.5412
9	9	1.	1.	1.
7.75	9	0.8611	1.	1.
7	9	0.7778	1.	1.103
6	9	0.6667	1.112	1.296
5	9	0.5556	1.207	1.613
4	9	0.4444	1.528	1.929
3	9	0.3333	1.789	2.217
2.6	9	0.2889	1.843	2.276
2	9	0.2222	1.492	1.845
1	9	0.1111	0.7849	0.9729
0.5	9	0.05556	0.4183	0.5172
7.75	7.75	1.	1.	1.
7	7.75	0.9032	1.	1.103
6	7.75	0.7742	1.112	1.296
5	7.75	0.6452	1.207	1.613
4	7.75	0.5161	1.528	1.929
3	7.75	0.3871	1.789	2.217
2.6	7.75	0.3355	1.843	2.276
2	7.75	0.2581	1.492	1.845
1	7.75	0.129	0.7849	0.9729
0.5	7.75	0.06452	0.4183	0.5172
7	7	1.	1.	1.
6	7	0.8571	1.112	1.174
5	7	0.7143	1.207	1.462
4	7	0.5714	1.528	1.748
3	7	0.4286	1.789	2.009
2.6	7	0.3714	1.843	2.063
2	7	0.2857	1.492	1.672
1	7	0.1429	0.7849	0.8817
0.5	7	0.07143	0.4183	0.4688
6	6	1.	1.	1.
5	6	0.8333	1.086	1.245
4	6	0.6667	1.375	1.489
3	6	0.5	1.609	1.711
2.6	6	0.4333	1.658	1.757
2	6	0.3333	1.342	1.424
1	6	0.1667	0.7061	0.751
0.5	6	0.08333	0.3763	0.3992
5	5	1.	1.	1.

4	5	0.8	1.266	1.195
3	5	0.6	1.482	1.374
2.6	5	0.52	1.526	1.411
2	5	0.4	1.236	1.144
1	5	0.2	0.6502	0.6031
0.5	5	0.1	0.3465	0.3206
4	4	1.	1.	1.
3	4	0.75	1.171	1.149
2.6	4	0.65	1.206	1.18
2	4	0.5	0.9765	0.9566
1	4	0.25	0.5137	0.5045
0.5	4	0.125	0.2738	0.2682
3	3	1.	1.	1.
2.6	3	0.8667	1.03	1.027
2	3	0.6667	0.8341	0.8322
1	3	0.3333	0.4388	0.4389
0.5	3	0.1667	0.2339	0.2333
2.6	2.6	1.	1.	1.
2	2.6	0.7692	0.8097	0.8106
1	2.6	0.3846	0.4259	0.4275
0.5	2.6	0.1923	0.227	0.2273
2	2	1.	1.	1.
1	2	0.5	0.526	0.5274
0.5	2	0.25	0.2804	0.2804
1	1	1.	1.	1.
0.5	1	0.5	0.533	0.5316
0.5	0.5	1.	1.	1.

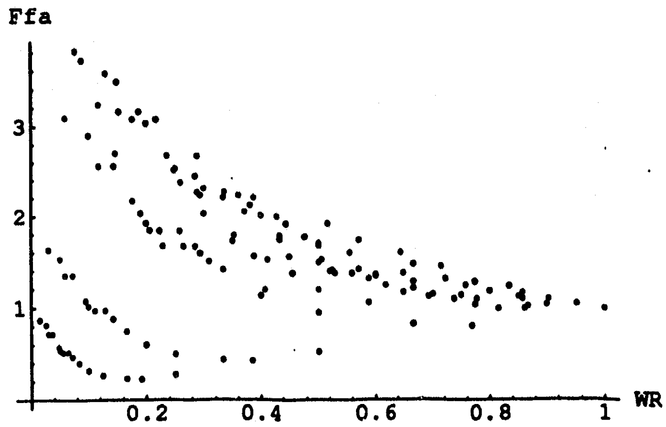
Plot the incerease in response, Ffa, versus the frequency ratio, wr.

```
FTR=
ListPlot[Transpose[{wr,FfaTR}],
    AxesLabel->{"WR","Ffa"},
    PlotJoined->False]
```



-Graphics-

```
FLO=
ListPlot[Transpose[{wr,FfaLO}],
     AxesLabel->{"WR","Ffa"},
     PlotJoined->False]
```



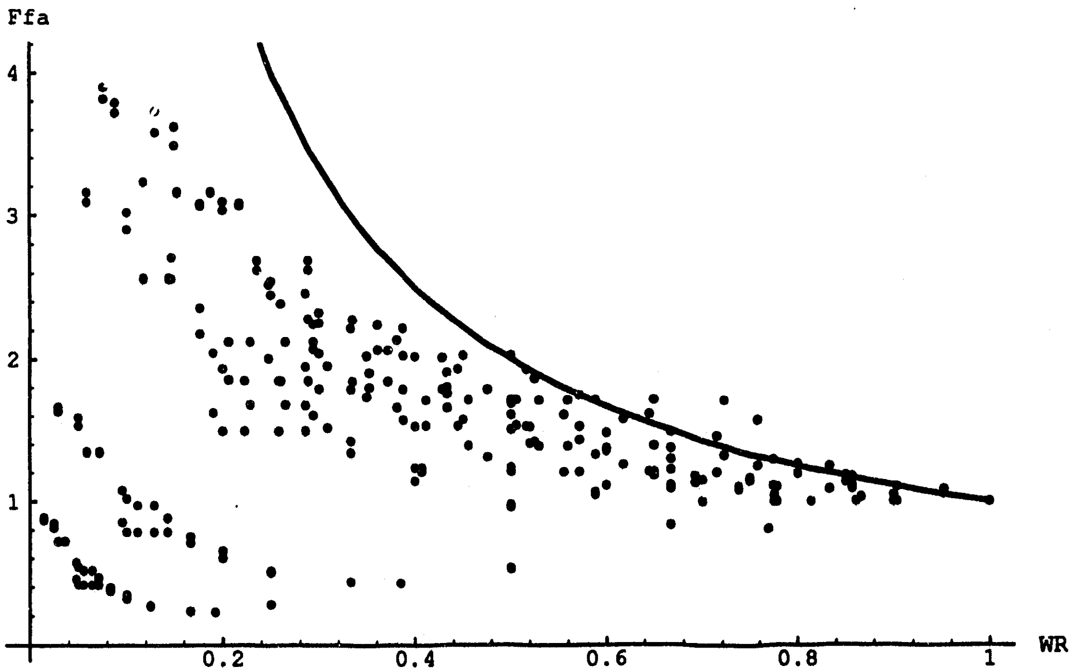
-Graphics-

Plot the inverse of the frequency ratio

```
Approx=Plot[1/w,{w,.1,1}];
```

Compare the calculated increase in response, Ffa, and 1/wr for both transverse and longitudinal accelerations

```
Show[FTR,FLO,Approx]
```

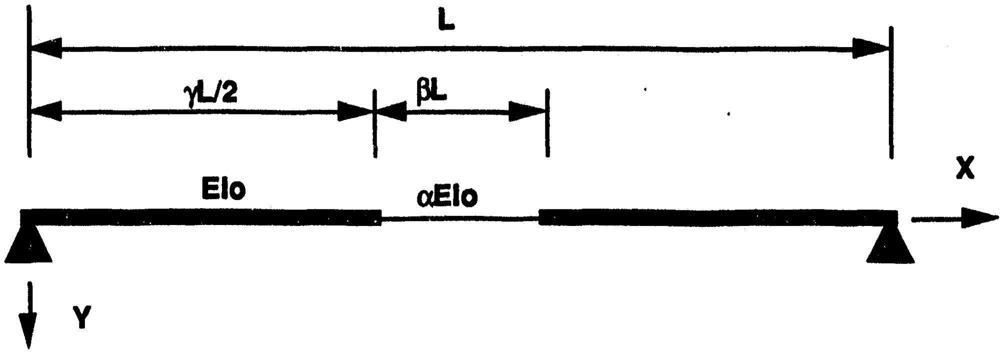


-Graphics-

Since most of the calculated increases in response, Ffa, fall below 1/wr, then 1/wr is an upper bound estimate of the actual increase in response, Ffa. Note that for most points, 1/wr is very conservative.

□ Shift in Natural Frequency Due to Corrosion

The ratio of the simple span beam's natural frequency, with a varying EI (due to corrosion) to the natural frequency of a simple span beam with a constant EI (uncorroded) is calculated. The Rayleigh method is used to calculate the natural frequency of the beam with a variable cross section. Mass is conservatively assumed to be constant along the length of the beam.



Ratio of natural frequencies of the beam with a varying cross section to the beam with a constant cross section, derived in Appendix E of WSRC-TR-92-236 is

```
wr[alpha_,gamma_]=(2*((EIo*((gamma*Pi^4*yo^2)/(4*L^3) -
          (Pi^3*yo^2*Sin[gamma*Pi])/(4*L^3) +
          alpha*((Pi^4*yo^2)/(4*L^3) -
             (gamma*Pi^4*yo^2)/(4*L^3) +
             (Pi^3*yo^2*Sin[gamma*Pi])/(4*L^3))))/
       (L*m*yo^2))^(1/2))/((EIo*Pi^4)/(L^4*m))^(1/2)
```

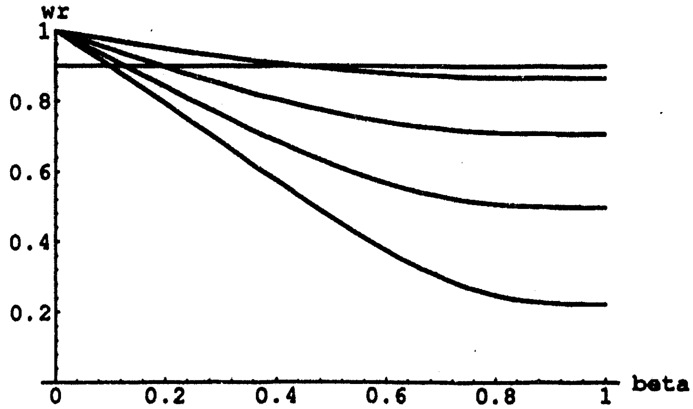
```
                         4   2      3   2
                 gamma Pi  yo     Pi  yo  Sin[gamma Pi]
(2 Sqrt[(EIo (---------------- - ------------------------ +
                        3                    3
                     4 L                  4 L

                     4   2              4   2      3   2
                   Pi  yo      gamma Pi  yo     Pi  yo  Sin[gamma Pi]
          alpha (---------- - --------------- + -------------------------))) /
                        3               3                     3
                     4 L             4 L                   4 L

                                     4
                 2            EIo Pi
       (L m yo )]) / Sqrt[-----------]
                                4
                               L  m
```

Plot of the ratio of natural frequencies of beams with a 75%, 50% and 25% of EIo versus beta.
Figure E.6 in WSRC-TR-92-236

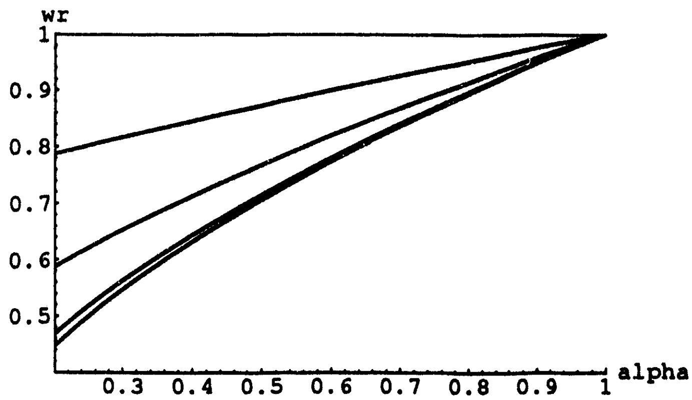
```
Plot[{.9,wr[.75,1-r],wr[0.5,1-r],wr[.25,1-r],wr[.05,1-r]},
        {r,.000001,1},PlotRange->{0,1},
        AxesLabel->{"beta","wr"}]
```



-Graphics-

Plot the ratio of natural frequencies of the beam with a varying cross section to the beam with a constant cross section, for different values of beta.

```
Plot[{wr[alpha,0],wr[alpha,0.25],
      wr[alpha,.5],wr[alpha,0.75],wr[alpha,1]},
        {alpha,0.20,1.0},
        PlotRange->{{0.2,1},{0.4,1}},
        AxesOrigin->{0.2,0.4},
        AxesLabel->{"alpha","wr"}]
```



-Graphics-

As shown in the previous section, the increase in response can be conservativley approximated by 1/wr.

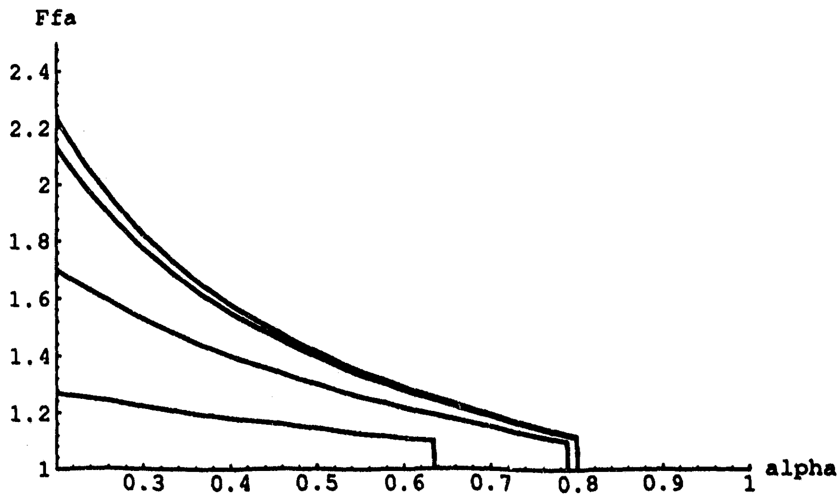
Define $F_{freq\ amp}$, as 1/wr, neglecting frequency changes less than 10%

```
Ffa[alpha_,gamma_]=
     If[alpha >= 0.8,
          1.0,
          If[ 1/wr[alpha,gamma] >= 1.1,
               1/wr[alpha,gamma],
               1.0
               ]
          ]
```

$$If[alpha >= 0.8, 1., If[\frac{1}{wr[alpha, gamma]} >= 1.1, \frac{1}{wr[alpha, gamma]}, 1.]]$$

Plot $F_{freq\ amp}$, for different values of beta versus alpha.

```
Plot[{Ffa[alpha,0],Ffa[alpha,0.25],
      Ffa[alpha,.5],Ffa[alpha,0.75],Ffa[alpha,1]},
        {alpha,0.20,1.0},
        PlotRange->{{0.2,1},{1,2.5}},
        AxesOrigin->{0.2,1},
        AxesLabel->{"alpha","Ffa"}]
```



-Graphics-

Development of the Locally Thinned Area Section Modulus Reduction Factor, R_{LTA}

Load plotting functions

```
<< Graphics`Graphics`
```

Define the angular variation in the thickness

Define the variation of thickness around the pipe circumference as

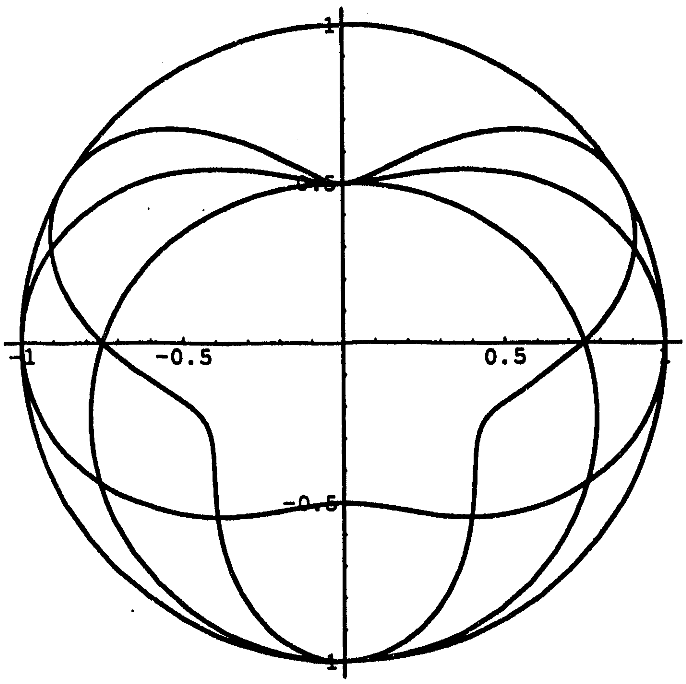
```
tt=t ( 1- b(1+Cos[c theta])/2 )
```

$$t\cdot\left(1 - \frac{b\ (1 + Cos[c\ theta])}{2}\right)$$

Where $t=t_{max}$ the maximum thickness, $b = (t_{max}-t_{min})/t_{max}$, and c is the number of regions less than t_{ave}.

Plot the thickness variation around the pipe
1) design thickness
2) b=0.5, c=1
3) b=0.5, c=2
4) b=0.5, c=3

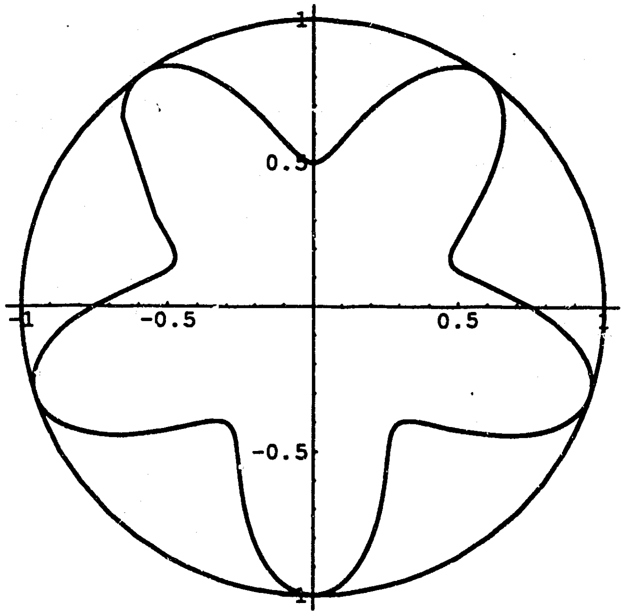
```
tt2=tt/t /.{b->0.5,c->1,theta->angle-Pi/2};
tt3=tt/t /.{b->0.5,c->2,theta->angle-Pi/2};
tt4=tt/t /.{b->0.5,c->3,theta->angle-Pi/2};
PolarPlot[{1,tt2,tt3,tt4},{angle,0,2Pi}]
```



-Graphics-

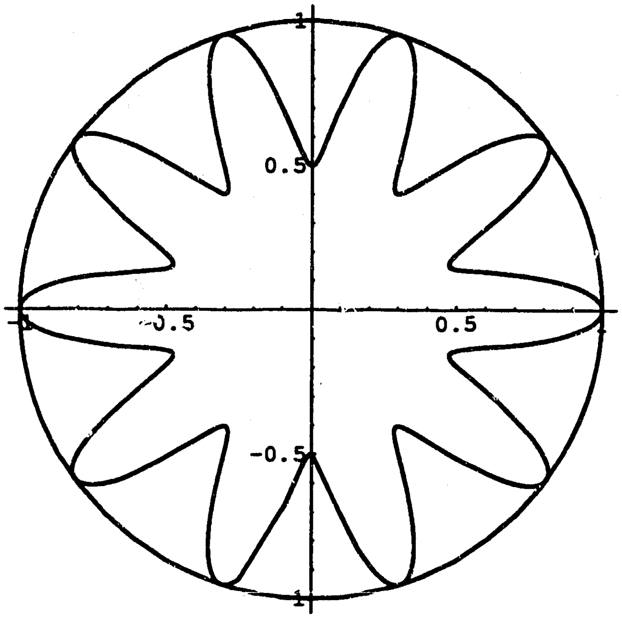
Plot the thickness variauon around the pipe
1) design thickness
2) b=0.5, c=5
3) b=0.5, c=10

```
tt2=tt/t /.{b->0.5,c->5,theta->angle-Pi/2};
PolarPlot[{1,tt2},{angle,0,2Pi}]
```



-Graphics-

```
tt2=tt/t /.{b->0.5,c->10,theta->angle-Pi/2};
PolarPlot[{1,tt2},{angle,0,2Pi}]
```



-Graphics-

▫ Cross Sectional Area

```
Area=2 Integrate[tt R,{theta,0,Pi}]
```

$$2 \left(\frac{(2 - b)\ Pi\ R\ t}{2} - \frac{b\ R\ t\ Sin[c\ Pi]}{2\ c}\right)$$

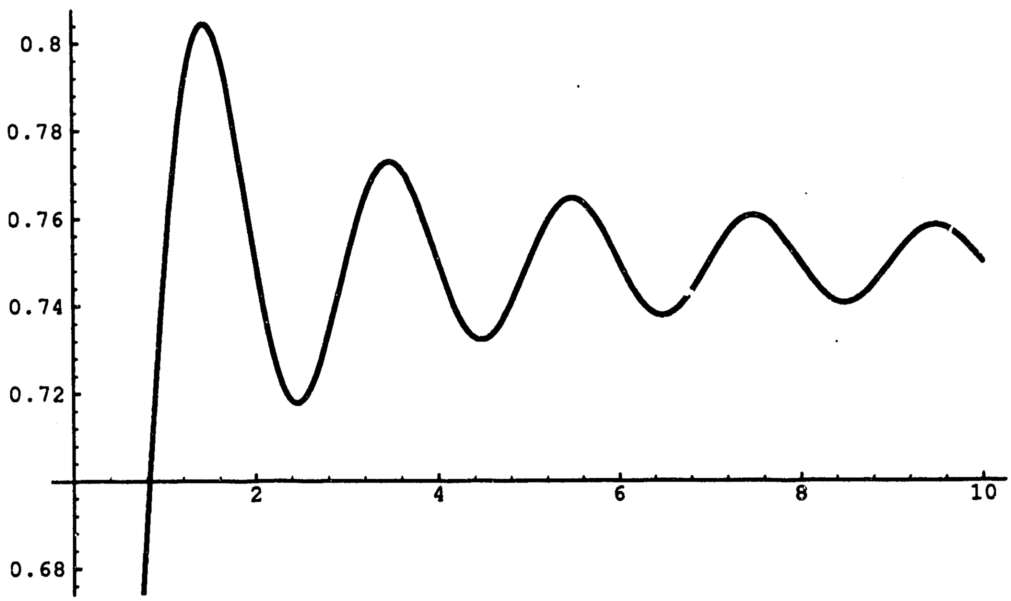
Average thickness

```
tave=Cancel[ Area/(2 Pi R) ]
```

$$\frac{2\ c\ Pi\ t - b\ c\ Pi\ t - b\ t\ Sin[c\ Pi]}{2\ c\ Pi}$$

Plot the average thickness as a function of c

```
Plot[(tave /t  /.{b->.5}),{c,.01,10}]
```



-Graphics-

▫ Center of gravity

```
AreaYbar=2 Integrate[tt R (R Cos[theta]),{theta,0,Pi}]
```

$$-\left(\frac{b\ c\ R^2\ t\ Sin[c\ Pi]}{1 - c^2}\right)$$

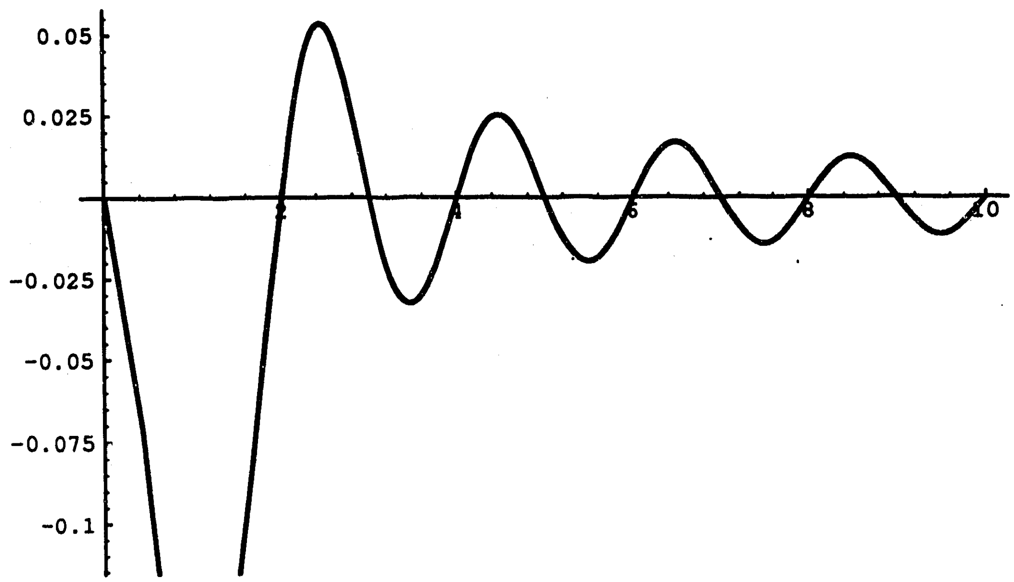
Distance to the center of gravity

```
Ybar=Cancel[ AreaYbar/Area ]
```

$$-\left(\frac{b\ c^2\ R\ Sin[c\ Pi]}{(-1 + c^2)\ (-2\ c\ Pi + b\ c\ Pi + b\ Sin[c\ Pi])}\right)$$

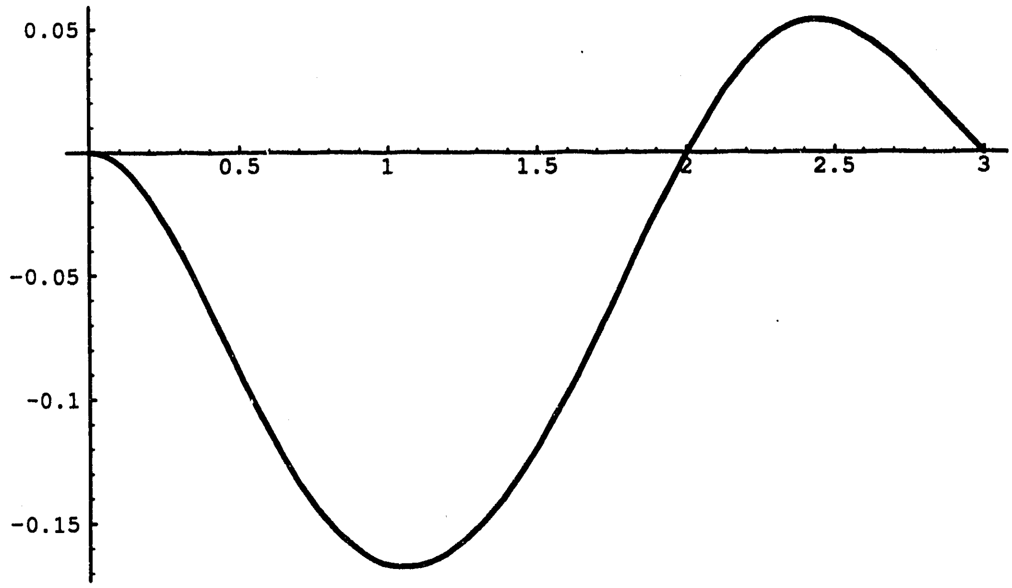
Plot Ybar/R for b=0.50, d=0

```
Plot[(Ybar/R /.{b->.5,d->0}),{c,.01,10}]
```



-Graphics-

```
Plot[(Ybar/R /.{b->.5,d->0}),{c,.01,3}]
```



-Graphics-

At a maximum value of |-0.167|, neglecting Area*Ybar^2 from the moment of inertia will change the results by less than

```
2 Pi R t (0.17 R)^2 / (Pi t R^3)
0.0578
```

or 5.8% for values of c below 2. For values of c>5, the results will change by less than

```
2 Pi R t (0.01 R)^2 / (Pi t R^3)
```

0.0002

or 0.02%.

▫ Moment of inertia

The moment of inertia about the X axis

```
I1=2 Integrate[tt R (R Cos[theta])^2,{theta,0,Pi}]
```

$$2\left(\frac{(2-b)\,Pi\,R^3\,t}{4} + \frac{b\,(4-2\,c^2)\,R^3\,t\,Sin[c\,Pi]}{4\,c\,(-4+c^2)}\right)$$

The moment of inertia about the neutral axis

```
Inertia=I1 - Area Ybar^2
```

$$\frac{-2\,b^2\,c^4\,R^2\,Sin[c\,Pi]^2\left(\frac{(2-b)\,Pi\,R\,t}{2} - \frac{b\,R\,t\,Sin[c\,Pi]}{2\,c}\right)}{(-1+c^2)^2\,(-2\,c\,Pi + b\,c\,Pi + b\,Sin[c\,Pi])^2} + 2\left(\frac{(2-b)\,Pi\,R^3\,t}{4} + \frac{b\,(4-2\,c^2)\,R^3\,t\,Sin[c\,Pi]}{4\,c\,(-4+c^2)}\right)$$

▫ Section Modulus

Section modulus for stress on the bottom of the pipe

```
Z1=Inertia/(R+Ybar)
```

$$\left(\frac{-2\,b^2\,c^4\,R^2\,Sin[c\,Pi]^2\left(\frac{(2-b)\,Pi\,R\,t}{2} - \frac{b\,R\,t\,Sin[c\,Pi]}{2\,c}\right)}{(-1+c^2)^2\,(-2\,c\,Pi + b\,c\,Pi + b\,Sin[c\,Pi])^2} + 2\left(\frac{(2-b)\,Pi\,R^3\,t}{4} + \frac{b\,(4-2\,c^2)\,R^3\,t\,Sin[c\,Pi]}{4\,c\,(-4+c^2)}\right)\right) \Big/ \left(R - \frac{b\,c^2\,R\,Sin[c\,Pi]}{(-1+c^2)\,(-2\,c\,Pi + b\,c\,Pi + b\,Sin[c\,Pi])}\right)$$

Section modulus for stress on the top of the pipe

```
Z2=Inertia/(R-Ybar)
```

$$\left(\frac{-2\,b^2\,c^4\,R^2\,Sin[c\,Pi]^2\left(\frac{(2-b)\,Pi\,R\,t}{2} - \frac{b\,R\,t\,Sin[c\,Pi]}{2\,c}\right)}{(-1+c^2)^2\,(-2\,c\,Pi + b\,c\,Pi + b\,Sin[c\,Pi])^2} + 2\left(\frac{(2-b)\,Pi\,R^3\,t}{4} + \frac{b\,(4-2\,c^2)\,R^3\,t\,Sin[c\,Pi]}{4\,c\,(-4+c^2)}\right)\right) \Big/ \left(R + \frac{b\,c^2\,R\,Sin[c\,Pi]}{(-1+c^2)\,(-2\,c\,Pi + b\,c\,Pi + b\,Sin[c\,Pi])}\right)$$

Section modulus of a pipe without local thinning (b=0)

```
Z1 /. {b->0,d->0}
```

$$\mathrm{Pi}\ R^2\ t$$

```
Z2 /. {b->0,d->0}
```

$$\mathrm{Pi}\ R^2\ t$$

▫ Ratio of thinned section modulus to $\pi\, t_{ave}\, R^2$.

Ratio for stresses on the bottom of the pipe

```
Ratio1= Z1/(Pi tave R^2)
```

$$\left(2\ c\ \left(\frac{-2\ b^2\ c^4\ R^2\ \mathrm{Sin}[c\ \mathrm{Pi}]^2\ \left(\frac{(2-b)\ \mathrm{Pi}\ R\ t}{2} - \frac{b\ R\ t\ \mathrm{Sin}[c\ \mathrm{Pi}]}{2\ c}\right)}{(-1+c^2)^2\ (-2\ c\ \mathrm{Pi} + b\ c\ \mathrm{Pi} + b\ \mathrm{Sin}[c\ \mathrm{Pi}])^2} + 2\ \left(\frac{(2-b)\ \mathrm{Pi}\ R^3\ t}{4} + \frac{b\ (4-2\ c^2)\ R^3\ t\ \mathrm{Sin}[c\ \mathrm{Pi}]}{4\ c\ (-4+c^2)}\right)\right)\right) \Big/ \left(R^2\ (2\ c\ \mathrm{Pi}\ t - b\ c\ \mathrm{Pi}\ t - b\ t\ \mathrm{Sin}[c\ \mathrm{Pi}])\ \left(R - \frac{b\ c^2\ R\ \mathrm{Sin}[c\ \mathrm{Pi}]}{(-1+c^2)\ (-2\ c\ \mathrm{Pi} + b\ c\ \mathrm{Pi} + b\ \mathrm{Sin}[c\ \mathrm{Pi}])}\right)\right)$$

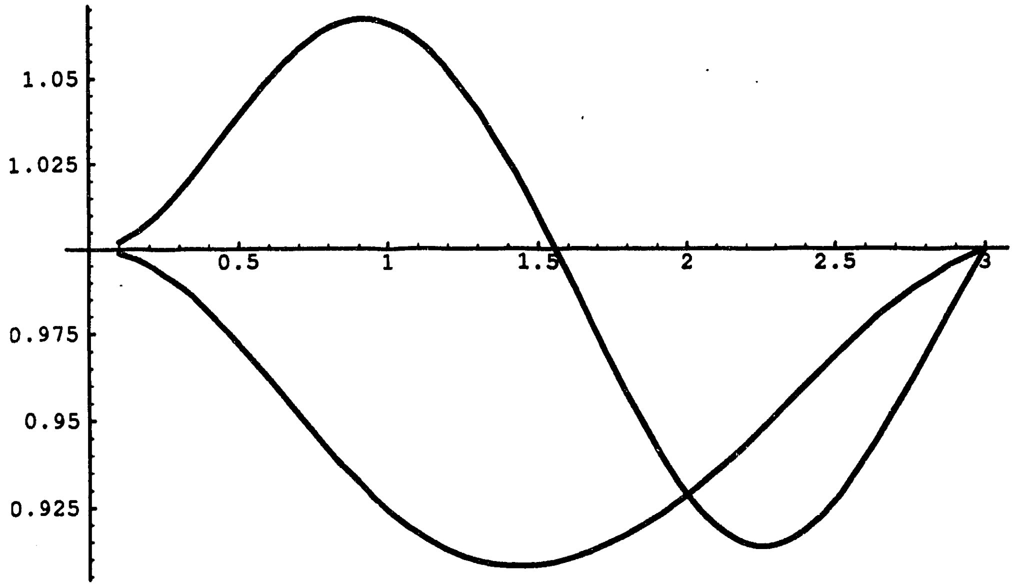
Ratio for stresses on the top of the pipe

```
Ratio2= Z2/(Pi tave R^2)
```

$$\left(2\ c\ \left(\frac{-2\ b^2\ c^4\ R^2\ \mathrm{Sin}[c\ \mathrm{Pi}]^2\ \left(\frac{(2-b)\ \mathrm{Pi}\ R\ t}{2} - \frac{b\ R\ t\ \mathrm{Sin}[c\ \mathrm{Pi}]}{2\ c}\right)}{(-1+c^2)^2\ (-2\ c\ \mathrm{Pi} + b\ c\ \mathrm{Pi} + b\ \mathrm{Sin}[c\ \mathrm{Pi}])^2} + 2\ \left(\frac{(2-b)\ \mathrm{Pi}\ R^3\ t}{4} + \frac{b\ (4-2\ c^2)\ R^3\ t\ \mathrm{Sin}[c\ \mathrm{Pi}]}{4\ c\ (-4+c^2)}\right)\right)\right) \Big/ \left(R^2\ (2\ c\ \mathrm{Pi}\ t - b\ c\ \mathrm{Pi}\ t - b\ t\ \mathrm{Sin}[c\ \mathrm{Pi}])\ \left(R + \frac{b\ c^2\ R\ \mathrm{Sin}[c\ \mathrm{Pi}]}{(-1+c^2)\ (-2\ c\ \mathrm{Pi} + b\ c\ \mathrm{Pi} + b\ \mathrm{Sin}[c\ \mathrm{Pi}])}\right)\right)$$

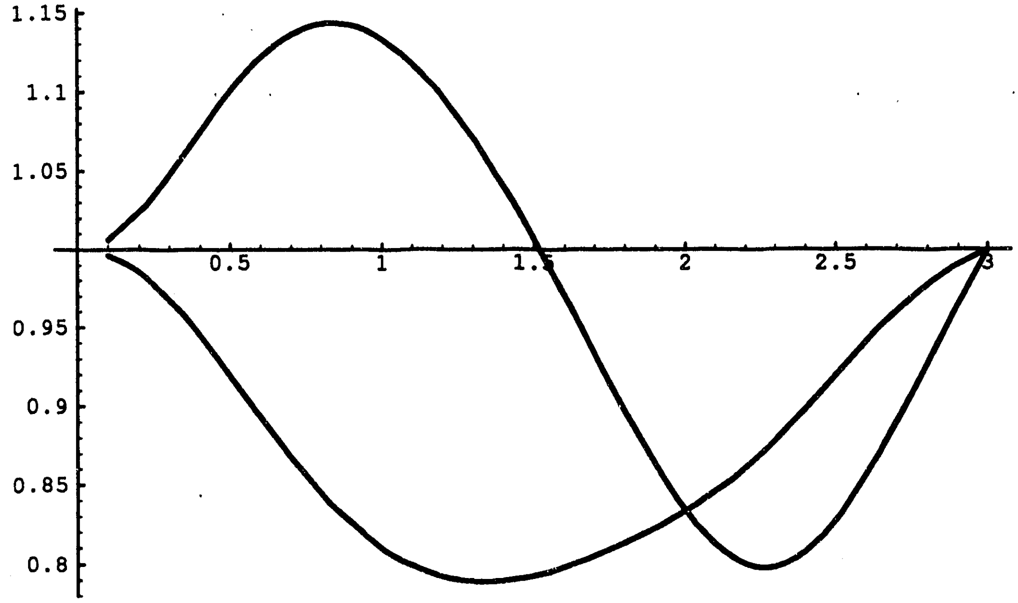
Plots of the Ratio of thinned section modulus to $\pi\, t_{ave}\, R^2$.

```
case=b->0.25
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,3}]
b -> 0.25
```




```
-Graphics-
```

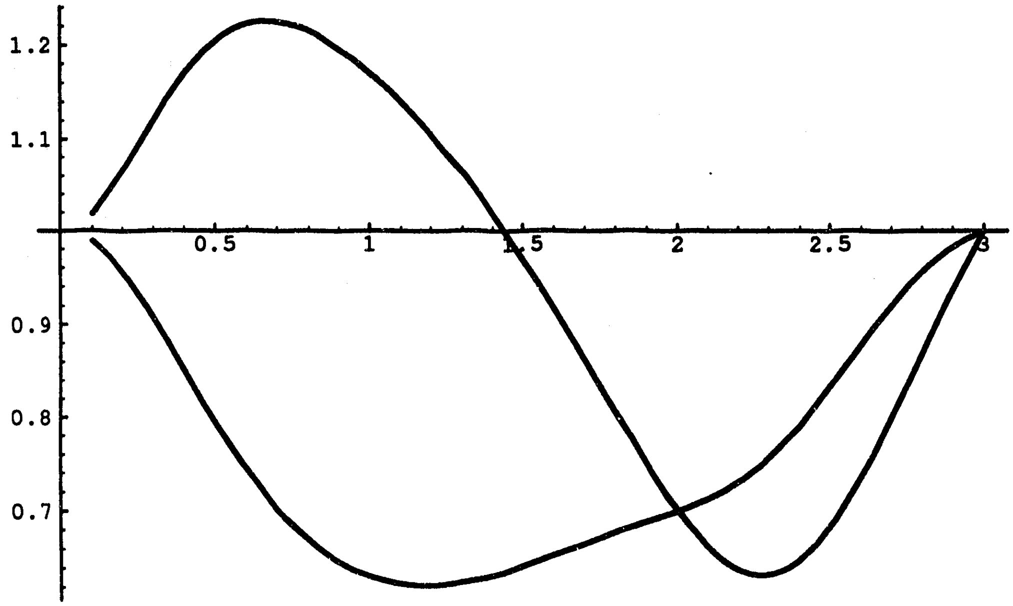
```
case=b->0.50
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,3}]
b -> 0.5
```




```
-Graphics-
```

```
case=b->0.75
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,3}]
```

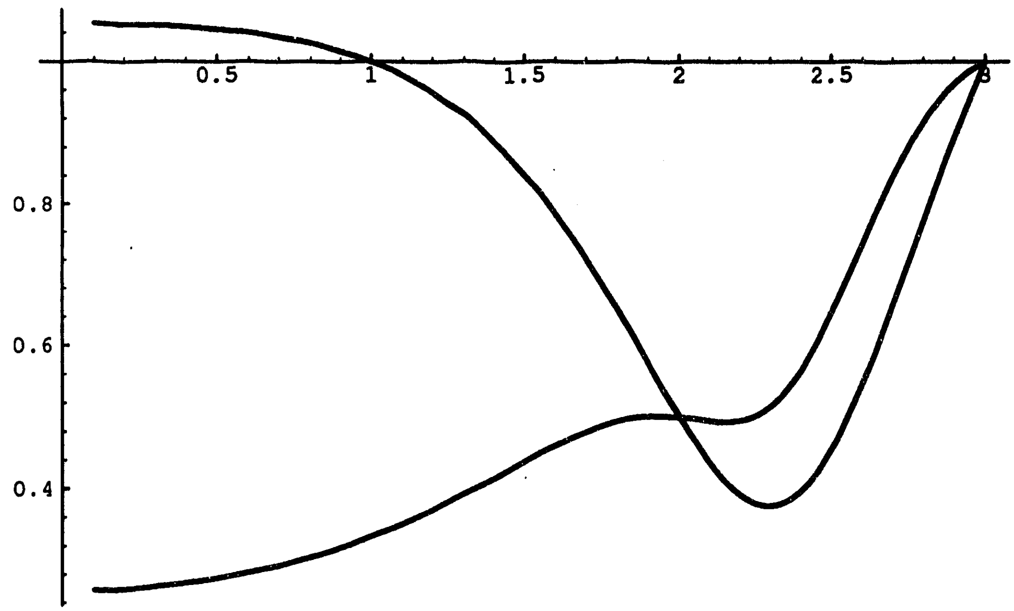
b -> 0.75



-Graphics-

```
case=b->1.00
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,3}]
```

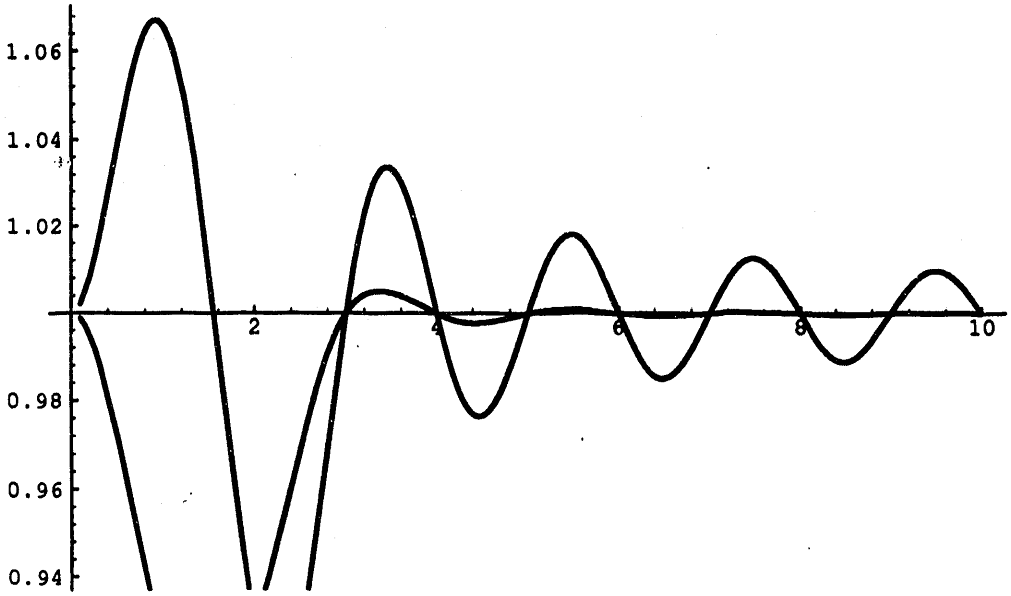
b -> 1.



-Graphics-

```
case=b->0.25
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,10}]
```

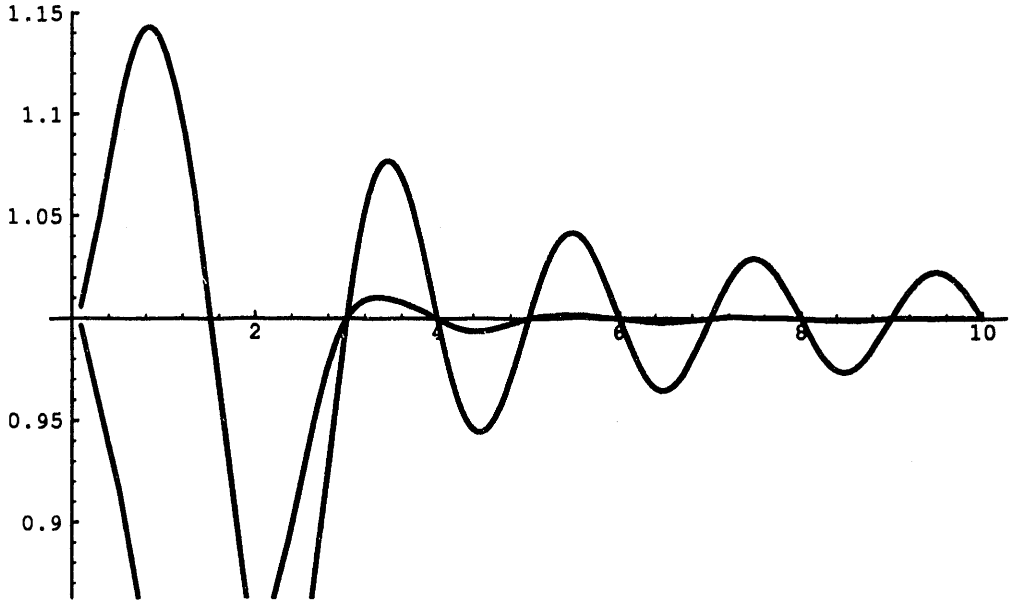
b -> 0.25



-Graphics-

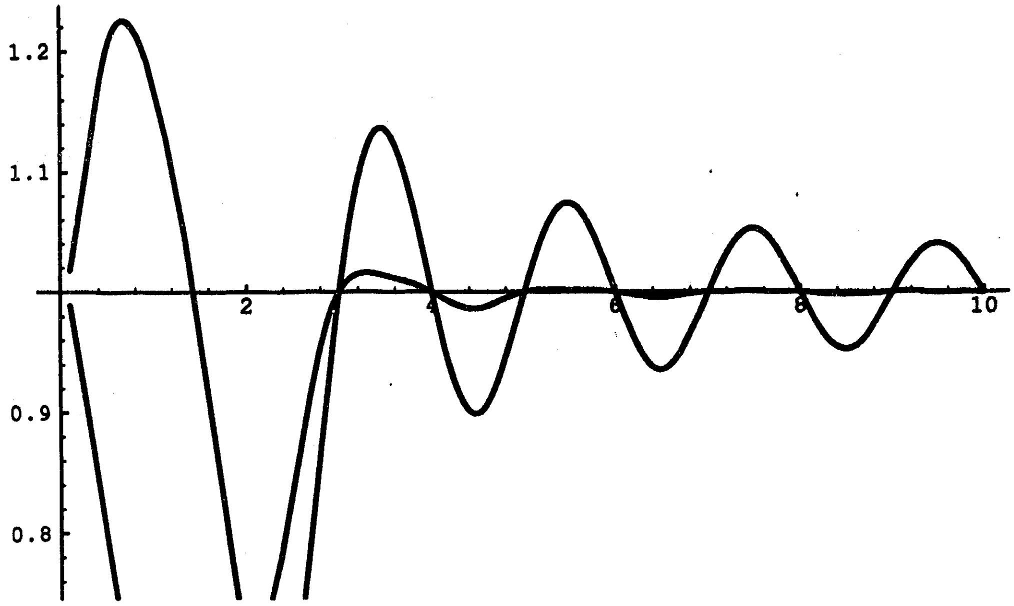
```
case=b->0.50
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,10}]
```

b -> 0.5



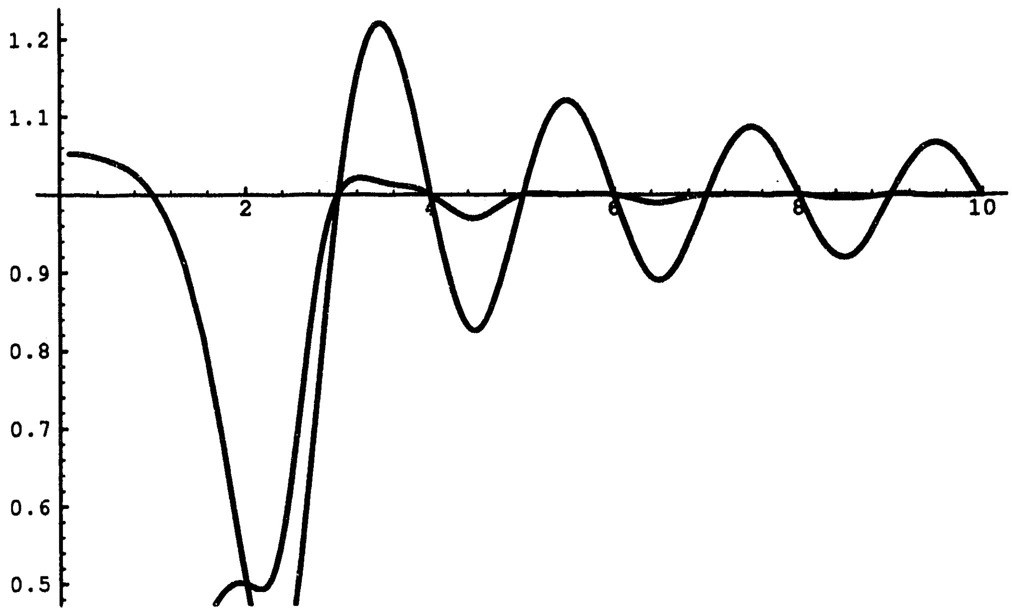
-Graphics-

```
case=b->0.75
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,10}]
b -> 0.75
```



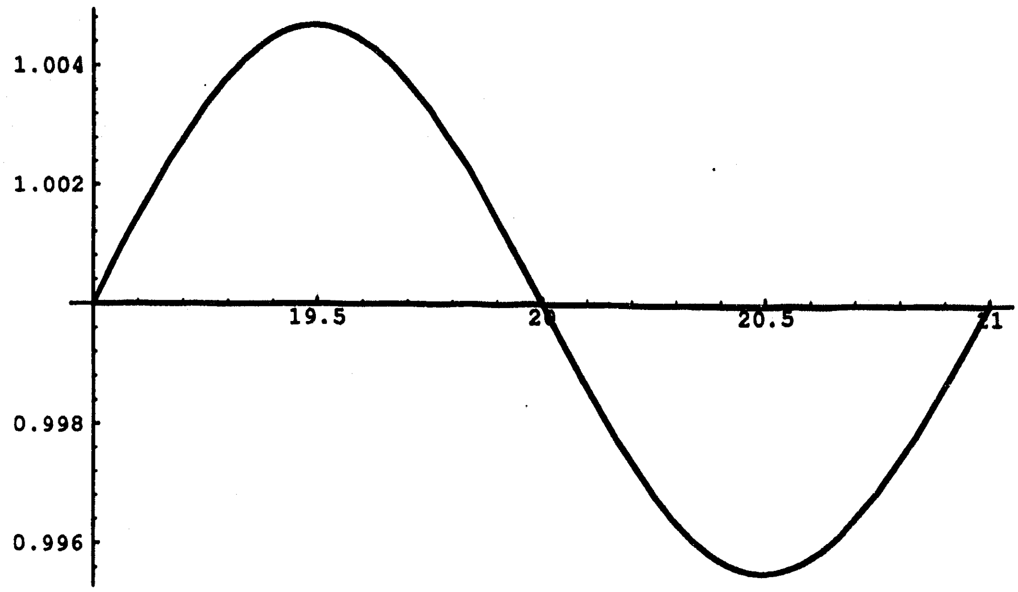

```
-Graphics-
```

```
case=b->1.00
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,0.1,10}]
b -> 1.
```

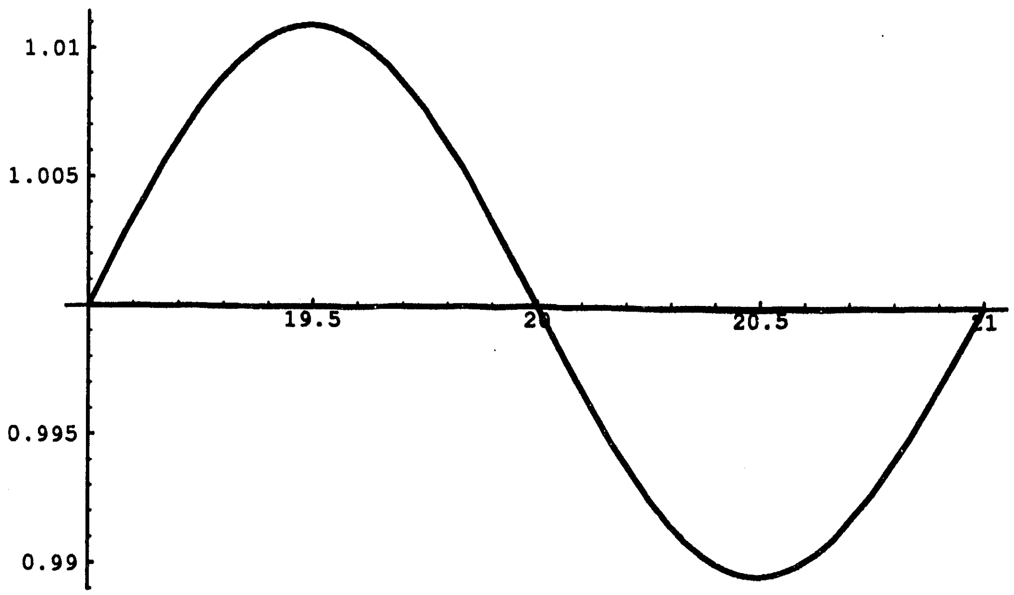



```
-Graphics-
```

```
case=b->0.25
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,19,21}]
b -> 0.25
```

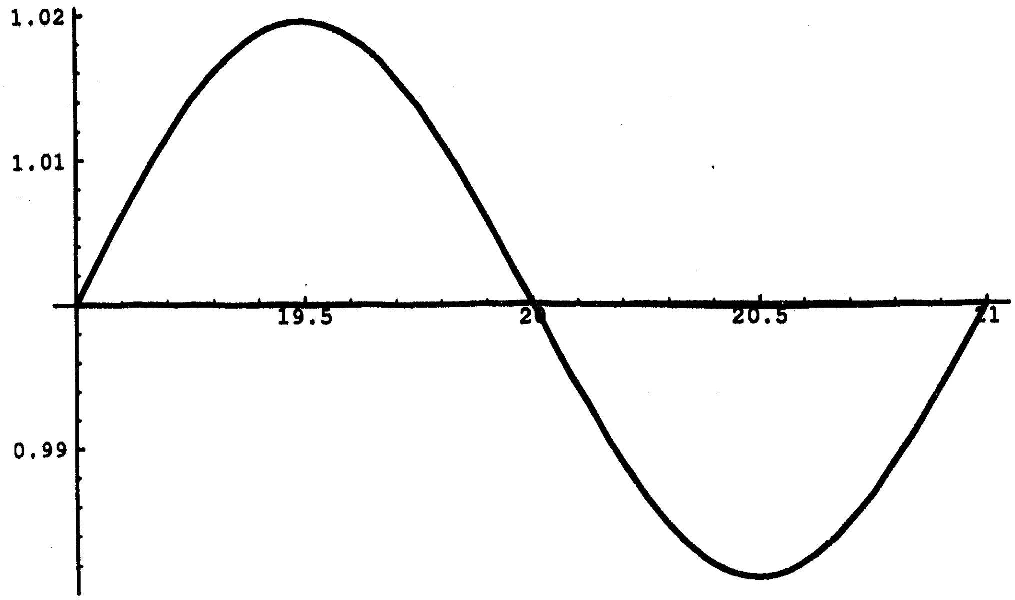



```
-Graphics-
case=b->0.50
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,19,21}]
b -> 0.5
```

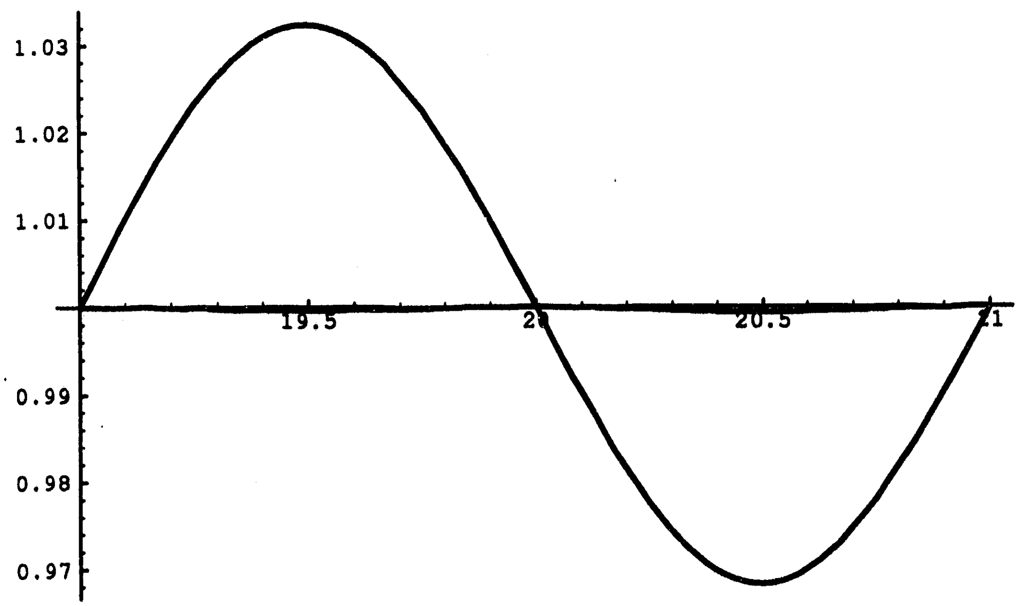



```
-Graphics-
```

```
case=b->0.75
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,19,21}]
b -> 0.75
```




```
-Graphics-
case=b->1.00
Plot[{(Ratio1 /.case),(Ratio2 /.case)},{c,19,21}]
b -> 1.
```




```
-Graphics-
```

□ Tabular Ratios of thinned section modulus to $\pi\, t_{ave}\, R^2$.

Simplify expressions for computational ease.

```
r1b25=Ratio1 /.b->0.25 //N ;
r2b25=Ratio2 /.b->0.25 //N ;
r1b50=Ratio1 /.b->0.50 //N ;
r2b50=Ratio2 /.b->0.50 //N ;
r1b75=Ratio1 /.b->0.75 //N ;
r2b75=Ratio2 /.b->0.75 //N ;
r1b100=Ratio1 /.b->1.00 //N ;
r2b100=Ratio2 /.b->1.00 //N ;
```

```
tab=Table[{c,1,
           Min[r1b25,r2b25],
           Min[r1b50,r2b50],
           Min[r1b75,r2b75],
           Min[r1b100,r2b100]},
           {c,0.1,0.9,0.1}];
TableForm[tab,
    TableHeadings->{{},
    {"c","b=0","b=0.25","b=0.50","b=0.75","b=1"}},
    TableSpacing->{0,5}]
```

c	b=0	b=0.25	b=0.50	b=0.75	b=1
0.1	1	0.998755	0.996265	0.988803	0.257436
0.2	1	0.99508	0.985262	0.956262	0.25951
0.3	1	0.989162	0.967721	0.907104	0.263002
0.4	1	0.981325	0.945064	0.849806	0.267961
0.5	1	0.97203	0.919291	0.792956	0.274455
0.6	1	0.961838	0.89261	0.742357	0.282573
0.7	1	0.951361	0.867018	0.700721	0.292413
0.8	1	0.941196	0.844051	0.668648	0.304086
0.9	1	0.931873	0.824712	0.645644	0.317697

```
tab=Table[{c,1,
           Min[r1b25,r2b25],
           Min[r1b50,r2b50],
           Min[r1b75,r2b75],
           Min[r1b100,r2b100]},
           {c,1.1,1.9,0.1}];
TableForm[tab,
    TableHeadings->{{},
    {"c","b=0","b=0.25","b=0.50","b=0.75","b=1"}},
    TableSpacing->{0,5}]
```

c	b=0	b=0.25	b=0.50	b=0.75	b=1
1.1	1	0.9173	0.798629	0.62297	0.351031
1.2	1	0.912507	0.791888	0.621198	0.370733
1.3	1	0.909478	0.788961	0.624427	0.392219
1.4	1	0.908164	0.789366	0.631616	0.415011
1.5	1	0.908447	0.792539	0.641675	0.438249
1.6	1	0.910172	0.797892	0.65345	0.460562
1.7	1	0.913176	0.804891	0.665795	0.480002
1.8	1	0.917313	0.813158	0.677762	0.494196
1.9	1	0.922471	0.822573	0.688958	0.501003

```
tab=Table[{c,1,
          Min[r1b25,r2b25],
          Min[r1b50,r2b50],
          Min[r1b75,r2b75],
          Min[r1b100,r2b100]},
          {c,2.1,2.9,0.1}];
TableForm[tab,
    TableHeadings->{{},
    {"c","b=0","b=0.25","b=0.50","b=0.75","b=1"}},
    TableSpacing->{0,5}]
```

c	b=0	b=0.25	b=0.50	b=0.75	b=1
2.1	1	0.919381	0.811904	0.66144	0.435665
2.2	1	0.91448	0.79978	0.63777	0.391158
2.3	1	0.914214	0.798287	0.632716	0.376148
2.4	1	0.918561	0.807809	0.648175	0.3972
2.5	1	0.927118	0.827643	0.683542	0.455301
2.6	1	0.939139	0.856043	0.735654	0.545098
2.7	1	0.953612	0.890457	0.799367	0.656319
2.8	1	0.96937	0.927896	0.868561	0.776595
2.9	1	0.985209	0.965327	0.937176	0.894237

```
tab=Table[{c,1,
          Min[r1b25,r2b25],
          Min[r1b50,r2b50],
          Min[r1b75,r2b75],
          Min[r1b100,r2b100]},
          {c,2.5,30.5,2}];

TableForm[tab,
    TableHeadings->{{},
    {"c","b=0","b=0.25","b=0.50","b=0.75","b=1"}},
    TableSpacing->{0,5}]
```

c	b=0	b=0.25	b=0.50	b=0.75	b=1
2.5	1	0.927118	0.827643	0.683542	0.455301
4.5	1	0.976562	0.944622	0.898526	0.826165
6.5	1	0.985006	0.964696	0.93563	0.890589
8.5	1	0.988854	0.973808	0.952383	0.919429
10.5	1	0.991098	0.979109	0.96209	0.936038
12.5	1	0.992579	0.9826	0.968465	0.946898
14.5	1	0.993632	0.98508	0.972985	0.954574
16.5	1	0.994422	0.986936	0.976363	0.960296
18.5	1	0.995036	0.988378	0.978985	0.96473
20.5	1	0.995527	0.989532	0.98108	0.968268
22.5	1	0.99593	0.990477	0.982793	0.971158
24.5	1	0.996265	0.991264	0.984221	0.973564
26.5	1	0.99655	0.991931	0.98543	0.975598
28.5	1	0.996794	0.992503	0.986466	0.977341
30.5	1	0.997006	0.992999	0.987364	0.978851

Ratio1 and Ratio2 are not defined at c=1 and c=2. Limits are used to evaluate these functions at c=1 and c=2.

```
Ratio1C1=Limit[Ratio1,c->1]
```

$$\frac{8 - 8 b + b^2}{8 - 10 b + 3 b^2}$$

```
Ratio2C1=Limit[Ratio2,c->1]
```

$$\frac{8 - 8 b + b^2}{8 - 6 b + b^2}$$

```
Ratio1C2=Limit[Ratio1,c->2]
```

$$\frac{-4 + 3 b}{2 (-2 + b)}$$

```
Ratio2C2=Limit[Ratio2,c->2]
```

$$\frac{-4 + 3 b}{2 (-2 + b)}$$

```
tab={{1,1,
        (Min[Ratio1C1,Ratio2C1] /.b->0.25),
        (Min[Ratio1C1,Ratio2C1] /.b->0.50),
        (Min[Ratio1C1,Ratio2C1] /.b->0.75),
        (Min[Ratio1C1,Ratio2C1] /.b->1.00)},
    {2,1,
        (Min[Ratio1C2,Ratio2C2] /.b->0.25),
        (Min[Ratio1C2,Ratio2C2] /.b->0.50),
        (Min[Ratio1C2,Ratio2C2] /.b->0.75),
        (Min[Ratio1C2,Ratio2C2] /.b->1.00)}};
TableForm[tab,
     TableHeadings->{{},
     {"c","b=0","b=0.25","b=0.50","b=0.75","b=1"}},
     TableSpacing->{0,5}]
```

c	b=0	b=0.25	b=0.50	b=0.75	b=1
1	1	0.92381	0.809524	0.630769	0.333333
2	1	0.928571	0.833333	0.7	0.5

■ *Mathematica* Functions

Definations of some *Mathematica* functions are given for reference.

```
? /.

expr /. rules applies a rule or list of rules in an attempt to transform each
   subpart of an expression expr.
```

?Cancel

```
Cancel[expr] cancels out common factors in the numerator and denominator of
   expr.
```

?Integrate

```
Integrate[f,x] gives the indefinite integral of f with respect to x.
   Integrate[f,{x,xmin,xmax}] gives the definite integral.
   Integrate[f,{x,xmin,xmax},{y,ymin,ymax}] gives a multiple integral.
```

?Limit

```
Limit[expr, x->x0] finds the limiting value of expr when x approaches x0.
```

?Plot

```
Plot[f, {x, xmin, xmax}] generates a plot of f as a function of x from xmin
   to xmax. Plot[{f1, f2, ...}, {x, xmin, xmax}] plots several functions fi.
```

?PolarPlot

```
PolarPlot[r, {t, tmin, tmax}] generates a polar plot of r as a function of t.
   PolarPlot[{r1, r2, ...}, {t, tmin, tmax}] plots each of the ri as a
   function of t on the same graph.
```

?Table

```
Table[expr, {imax}] generates a list of imax copies of expr. Table[expr, {i,
   imax}] generates a list of the values of expr when i runs from 1 to imax.
   Table[expr, {i, imin, imax}] starts with i = imin. Table[expr, {i, imin,
   imax, di}] uses steps di. Table[expr, {i, imin, imax}, {j, jmin, jmax},
   ...] gives a nested list. The list associated with i is outermost.
```

?TableForm

```
TableForm[list] prints with the elements of list arranged in an
   array of rectangular cells.
```

Wall Thinning Worksheet

Line ____________________

Diameter = ____________ $t_{nominal}$ = ______________

Disposition Summary

	Pass	Fail
Screening Criteria		
Uniform Thinning Criteria		
Local Thinning Criteria		
Pitting Criteria		
Acceptance by Additional Analysis		
Pipe is acceptable for continued use		

Summary of UT Data

$t_{min\ meas}$ = ____________ $t_{max\ meas}$ = ____________

$t_{average\ meas}$ =__________ $t_{std\ dev}$ = ______________

Reference:____

Reference Page #_______ Point ID #_____________

Screening Criteria

$t_{min\ meas}$ = ____________ $\geq$ 0.875 $t_{nominal}$ = ________________

If $t_{min\ meas} \geq$ 0.875 $t_{nominal}$ then stop, pipe is acceptable for continued service OK___

If not $t_{min\ meas} <$ 0.875 $t_{nominal}$ then continue with work sheet ___

Wall Thinning Worksheet

Summary of Stress Report

Node Number__________ Stress ________________

Reference:____

Calculate the Required Uniform Wall Thicknesses

$t_{req\ uniform\ hoop}$ =________

$t_{req\ SEP\text{-}24}$ =__________

$t_{req\ Fracture}$ =__________ } $t_{req\ uniform\ axial}$ =__________

$t_{req\ Stability}$ =__________

Reference: WSRC-TR-92-236

Uniform Thinning Criteria

$$\alpha = \frac{\text{average measured thickness (over 360°)}}{\text{design thickness}} = \_\_\_\_\_\_\_\_\_\_ = \_\_\_\_\_\_$$

$$\beta = \frac{\text{length of thinner portion}}{\text{span length}} = \_\_\_\_\_\_\_\_\_\_ = \_\_\_\_\_\_$$

$$\text{If } \beta \le \begin{cases} \dfrac{0.1}{1-\alpha} & \text{when } \alpha < 0.8 \\ 1.0 & \text{when } \alpha \ge 0.8 \end{cases} = \_\_\_\_\_\_$$

then $F_{freq\ amp}$ = 1.0

else determine $F_{freq\ amp}$ from Fig 1[1]

$F_{freq\ amp}$ = __________

(A) $t_{min\ meas}$ = ______________ $\geq$ $t_{req\ uniform\ hoop}$ = __________

(B) $t_{min\ meas}$ = ______________ $\geq$ $t_{req\ uniform\ hoop} \times F_{freq\ amp}$ = __________

If the both inequalities A and B is true, then the corrosion criteria has been met, OK_____

If either A or B is false then the corrosion criteria has not been met,

Continue with work sheet

Wall Thinning Worksheet

Local Thinning Criteria

If one of the hoop stress criteria is met and one of the axial stress criteria is met then the corrosion criteria has been met, OK___
If either the hoop stress or axial stress criteria are not met then the corrosion criteria has not been met. Continue with work sheet

Hoop Stress Criteria

(A) $t_{min\ meas}$ = ____________ ≥ $t_{req\ uniform\ hoop}$ = ____________
If $t_{min\ meas} \geq t_{req\ uniform\ hoop}$ then the hoop stress criteria has been met, OK___

B) $\frac{Lm(a)}{\sqrt{Rt_{average\ meas}}}$ = ____________ = ____________

t_{aloc} = ____________ from Curve 1 of Figure 4

$t_{min\ meas}$ = ____________ ≥ t_{aloc} = ____________
If $t_{min\ meas} \geq t_{aloc}$ then the hoop stress criteria has been met, OK___

C) Lm = ____________ L = ____________ (see Figure 4)

(1) $\frac{t_{min\ meas}}{t_{req\ uniform\ hoop}}$ = ____________

$\geq \frac{1.5\sqrt{R\ t_{req\ uniform\ hoop}}}{L}\left[1 - \frac{t_{nominal}}{t_{req\ uniform\ hoop}}\right] + 1.0$ = ____________

(2) $\frac{t_{min\ meas}}{t_{req\ uniform\ hoop}}$ = ____________

$\geq \frac{0.353\ L_m}{\sqrt{R\ t_{req\ uniform\ hoop}}}$ = ____________

(3) $t_{nominal}$ = ____________ > 1.13 $t_{req\ uniform\ hoop}$ = ____________

(4) L_m = ____________ < $2.65\sqrt{R\ t_{req\ uniform\ hoop}}$ = ____________

Wall Thinning Worksheet

If the inequalities in (1) through (4) are all met then the hoop stress criteria has been met, OK__

Axial Stress Criteria

A) $t_{min\ meas}$ = __________ $\geq$ $t_{req\ uniform\ axial} \times F_{freq\ amp}$ = __________

If $t_{min\ meas} \geq t_{req\ uniform\ axial} \times F_{freq\ amp}$ then the axial stress criteria has been met, OK__

B) Get $L_{t<t_{ave}}$ from P-Scan data, $L_{t<t_{ave}}$ = __________

$$\frac{L_{t<t_{ave}}}{\text{Diameter}} = \_\_\_\_\_\_ = \_\_\_\_\_\_$$

(1) $t_{average\ meas}$ = __________

$\geq t_{req\ uniform\ axial} \times F_{freq\ amp} / R_{LTA}$ = __________

(2) $\frac{L_{t<t_{ave}}}{\text{Diameter}}$ = __________ ≤ 1.57

If the inequalities in (1) and (2) are met, then the axial stress criteria has been met, OK__

C) Calculate $t_{req\ non\text{-}uniform\ axial}$ using the actual thinned geometry from P-Scan data, $t_{req\ non\text{-}uniform\ axial}$ = __________

$t_{min\ meas}$ = __________ $\geq$ $t_{req\ non\text{-}uniform\ axial} \times F_{freq\ amp}$ = __________

If $t_{min\ meas} \geq t_{req\ non\text{-}uniform\ axial} \times F_{freq\ amp}$, then the axial stress criteria has been met, OK__

Wall Thinning Worksheet

Pitting Criteria

Estimated average pit radius, r_{pit} = ________

Number of pits in a sample area = ________

Size of Sample Area =________

$$\rho = \pi\, r_{pit}^2 \times \frac{\text{Number of pits}}{\text{Sample Area}} = \underline{\hspace{3cm}}$$

$$R_{pit} = \left(1 - \sqrt{\frac{4\rho}{\pi}}\right) = \underline{\hspace{4cm}}$$

A) $t_{base\ meas}$ = ______ $\geq t_{req\ uniform\ hoop} / R_{pit}$ = __________

B) $t_{base\ meas}$ = ______ $\geq t_{req\ uniform\ axial} \times F_{freq\ amp} / R_{pit}$ = ______

If the both inequalities A and B are true, then the corrosion criteria has been met, OK___

If either A or B is false then the corrosion criteria has not been met

DATE
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7 / 19 / 93