BELLOWS EXPANSION JOINT
DESIGN EVALUATION
DRYWELL PENETRATION X-25
QUAD CITIES NUCLEAR POWER STATION
UNIT 1

Prepared for
COMMONWEALTH EDISON COMPANY
Quad Cities Nuclear Power Station
Chicago, Illinois 60690

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Section 1 - 7 pages
Calculations - 4 pages
Section 2 - 16 pages

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Fracture Mechanics Evaluation

In order to perform a fracture mechanics evaluation, one needs the material fracture toughness, yield strength, elastic modulus and crack growth rate. The number of stress cycles over a given time interval and the stress range associated with these cycles are also needed. The effect of adverse environmental conditions is generally represented as an increased crack growth rate and/or decreased fracture toughness, as appropriate.

For the Quad Cities Nuclear Power Station Unit 1 penetration X-25 bellows, we want to determine:

1. The critical crack length for a meridional (longitudinal) through crack.
2. The number of cycles required for a meridional through crack 1.7 inches long to grow to critical crack length with a conventional austenitic stainless crack growth rate.
3. The critical crack length for a circumferential through crack.
4. The number of cycles required for a string of equally spaced pinhole through cracks to grow to critical crack length with a conventional austenitic stainless growth rate.

The penetration X-25 bellows has a 1.7 inches long meridional (longitudinal) crack over one of its convolutions. It has been replaced because of its excessive (137 SCFH) leak rate. The largest crack in any remaining bellows should be much smaller than 1.7 inches based upon the leak rate test results. This bellows has also been reported to have many smaller through cracks. Most of these are pinhole cracks.

A review of the size, configuration and design movements of all penetration bellows indicates the X-25 penetration bellows is one of the most highly stressed, along with bellows for penetrations X-12, X-14, X-16A and X-16B. The penetration X-16A and X-16B bellows have been recently replaced because they leaked excessively. Hence, the penetration X-25 bellows, with its 1.7 inches long meridional crack, is believed to represent a worst case condition. Work is currently in progress to evaluate the designs of the other bellows in detail.

Material Properties

Section VIII of the ASME Boil-r and Pressure Vessel Code gives the minimum yield strength of 304 stainless steel as 30 ksi and the elastic modulus as 28.3×10^6 psi. Rolfe and Barsom, "Fracture and Fatigue Control in Structures", gives the crack growth rate for austenitic stainless steel as

$$da/dN = 3.0 \times 10^{-10} \ (\Delta K)^{3.25},$$

where a is in inches and ΔK is in ksi$\sqrt{\text{in.}}$.

A fracture toughness of 105 ksi$\sqrt{\text{in.}}$ to represent degraded 304 stainless steel was calculated from typical Charpy keyhole impact test data in United States Steel's "Steels for Elevated Temperature Service" conservatively accounting for the difference between Charpy keyhole-notch and V-notch specimens and using the upper shelf correlation equation in Rolfe and Barsom. Material toughness degradation was conservatively assumed to be similar to that resulting from long term exposure to temperatures above 800°F.

304 stainless is ductile at room temperature with typical Charpy keyhole-notch impact values of 89 to 91 ft-lb. Room temperature impact values are significantly lower when tested after long time exposure to temperatures above 800°F. Although the bellows have not been exposed to this type of environment, it was judged conservative to base the fracture toughness on the 47 ft-lb typical Charpy keyhole-notch value after 10,000 hours at 1200°F.

Loading

The number of stress cycles for which the bellows have been rated over a thirty year lifetime and over one plant cycle (eighteen months) are:

30 years		one plant cycle
20	pressure cycle 0 to 65 psig range	1
20	pressure cycles -48 to 0 psig range	1
4900	pressure cycles 4 psig range (±2 psig)	245
4900	lateral motion cycles 0 to 1.785 inches range	245
	or lateral motion cycles 0 to 1.0239 inch range	

Since internal pressure is positive, the -48 psig local leak rate test pressure represents external pressure applied to the inner ply of the bellows. The outer bellows would be subjected to a +48 psig pressure during this test. It has been reported that the actual number of lateral motion cycles due to temperature transients is equivalent to about forty per plant cycle.

This analysis conservatively uses the 1.785 inches lateral motion based upon the accident condition which brackets the LOCA. Note that although lateral motion and pressure stresses are calculated

for the worst case inner ply of the bellows, outer ply lateral motion and pressure stresses would be similar. Calculations are also repeated for comparison using the 1.0239 inch lateral motion based upon design operating cycles. Seismic events are not explicitly considered in the analysis because the bellows stresses associated with such events are small relative to the conservatisms in the calculations.

Meridional stresses are stresses in the plane of the bellows convolution shell including both the axial and radial directions. Meridional stresses tend to open circumferential cracks while hoop (circumferential) stresses tend to open meridional cracks. These are illustrated in the figure on page 7.

The per cycle stress range associated with each of these loadings was calculated using equations in the 1980 edition of the Standards of the Expansion Joint Manufacturers Association, Inc. The large range test pressure cycles were combined into cycles from -48 psig to +65 psig. The meridional stress ranges are:

pressure cycle 113 psig range	18,200 psi range
pressure cycle 4 psig range	650 psi range
lateral motion cycle 1.785 inches range	85,000 psi range
lateral motion cycle 1.0239 inch range	48,800 psi range

The stress ranges indicate that crack propagation over one plant cycle will be driven by the 245 lateral motion cycles since the low pressure oscillations have a very small stress range and there is only one 113 psig pressurization cycle. The range of circumferential stress for these cycles are:

lateral motion cycle 1.785 inches range	75,000 psi range
lateral motion cycle 1.0239 inch range	43,000 psi range

The 75 ksi and 85 ksi stress ranges are more than twice the 30 ksi minimum or the 32.2 ksi typical yield strengths of the material. This indicates the first half of a lateral motion cycle will exceed yield and produce some plastic deformation. Subsequent lateral motion cycling goes between an elastically calculated -37.5 ksi and an elastically calculated +37.5 ksi for a meridional crack and between an elastically calculated -42.5 ksi and an elastically calculated +42.5 ksi for a circumferential crack. This is not unexpected; the EJMA Standards state, "The major stresses in a bellows result from the effects of pressure and deflection. Normally the deflection stresses are higher than pressure stresses, generally above the yield point of the bellows material, and are meridional."

The bellows fatigue curves for austenitic stainless steel in the EJMA Standards state, "These curves are intended to predict **average** fatigue life at ambient temperature for austenitic stainless steel bellows which have not been heat treated. They

are considered valid primarily in the range of 10^3 to 10^6 cycles, due to the limited data available for the very low and very high cyclic ranges. The equations are of the form provided in 'Design of Pressure Vessels for Low Cycle Fatigue' by B. F. Langer, ASME paper 61-WA-18. The constants were modified to reflect the experience of EJMA members for bellows fatigue life." Using the 85 ksi total stress range found by design equations of the EJMA Standards with this curve results in a prediction of 1.15×10^5 cycles of operation.

Critical meridional through crack length

The critical meridional through crack length is 4.991 inches. This value is much lower than one might expect for such a ductile material, reflecting the conservatism of the fracture toughness used in the calculation. It also reflects the conservatism of the 1.785 inches lateral displacement. The critical crack length using the 1.0239 inch lateral displacement is 7.799 inches.

Number of cycles for a meridional through crack 1.7 inches long to grow to critical crack length

Using the same conservative input data, there are 363 lateral displacement cycles between 1.7 inches and critical crack length. This is about one and a half times the 245 design displacement cycles in one plant cycle. The increase in crack length over a plant cycle due to transgranular stress corrosion cracking is shown on page 6 to be no more than 0.1864 inch. If the fracture mechanics calculation is repeated using an augmented crack length to account for this growth, there are 316 lateral displacement cycles between 1.8864 inches and critical crack length. This is about one and a quarter times the 245 design displacement cycles in one plant cycle. Note that the bellows with the meridional crack 1.7 inches long is being replaced because of its 137 SCFH leak rate; the largest meridional crack in any remaining bellows should be much smaller than 1.7 inches and require even more time to attain critical length. There are 2,771 lateral displacement cycles between 1.7 inches and critical crack length using the 1.0239 inch lateral displacement. This is more than eleven times the 245 design displacement cycles in one plant cycle.

Critical circumferential through crack length

The critical circumferential through crack length is 3.886 inches. This value is much lower than one might expect for such a ductile material, reflecting the conservatism of the fracture toughness used in the calculation. It also reflects the conservatism of the 1.785 inches lateral displacement. The

critical circumferential through crack length using the 1.0239 inch lateral displacement is 7.799 inches.

Assessment of a string of pinhole cracks

One additional issue will be addressed; a bellows convolution with several pinholes equally spaced along its entire circumference. This calculation conservatively assumes that they are larger and far more numerous than have been reported. Each pinhole is conservatively considered to be a through crack 1/8 inch long.

The stress intensity factor for a row of equal length collinear through cracks was obtained from the Handbook of Stress-Intensity Factors for Researchers and Engineers published by Lehigh University. The variable coefficient of the stress intensity factor depends upon the size, pitch and the number of cracks. Since parametric curves are provided for this coefficient for 3, 5, 7, 11 and an infinite number of cracks, the coefficient was obtained from the curve for an infinite number.

Although, as expected, the critical crack length for this case is smaller than for a single crack, there are 2,077 displacement cycles between 1/8 inch and critical crack length. This is about eight and a half times the 245 design displacement cycles in one plant cycle. There are 13,225 displacement cycles between 1/8 inch and critical crack length using the 1.0239 inch lateral displacement. This is about fifty-seven times the 245 design displacement cycles in one plant cycle.

Conclusions

The preceding extremely conservative calculations demonstrate that using a bellows with a meridional crack 1.7 inches long through one additional plant cycle would not result in its catastrophic failure. They also demonstrate that a bellows convolution with several 1/8 inch long "pinhole" cracks equally spaced along its circumference will not fail catastrophically in one plant cycle. Slightly more realistic calculations using the 1.0239 inch lateral displacement show substantially greater margins to failure.

Local leak rate test data are much more useful to quantify the extent of cracking in the bellows than dye penetrant examination results. Since only the outer surface of the two-ply bellows can be examined, the dye penetrant test can reveal nothing about the condition of the inner ply.

Transgranular Stress Corrosion Cracking

Corrosion is an electrochemical process; "electro" because an electrical current is involved, "chemical" because a chemical reaction occurs. Stress corrosion is the initiation and propagation of cracks under the simultaneous influence of stress and corrosion. Chloride cracking of austenitic stainless steel is a common example.

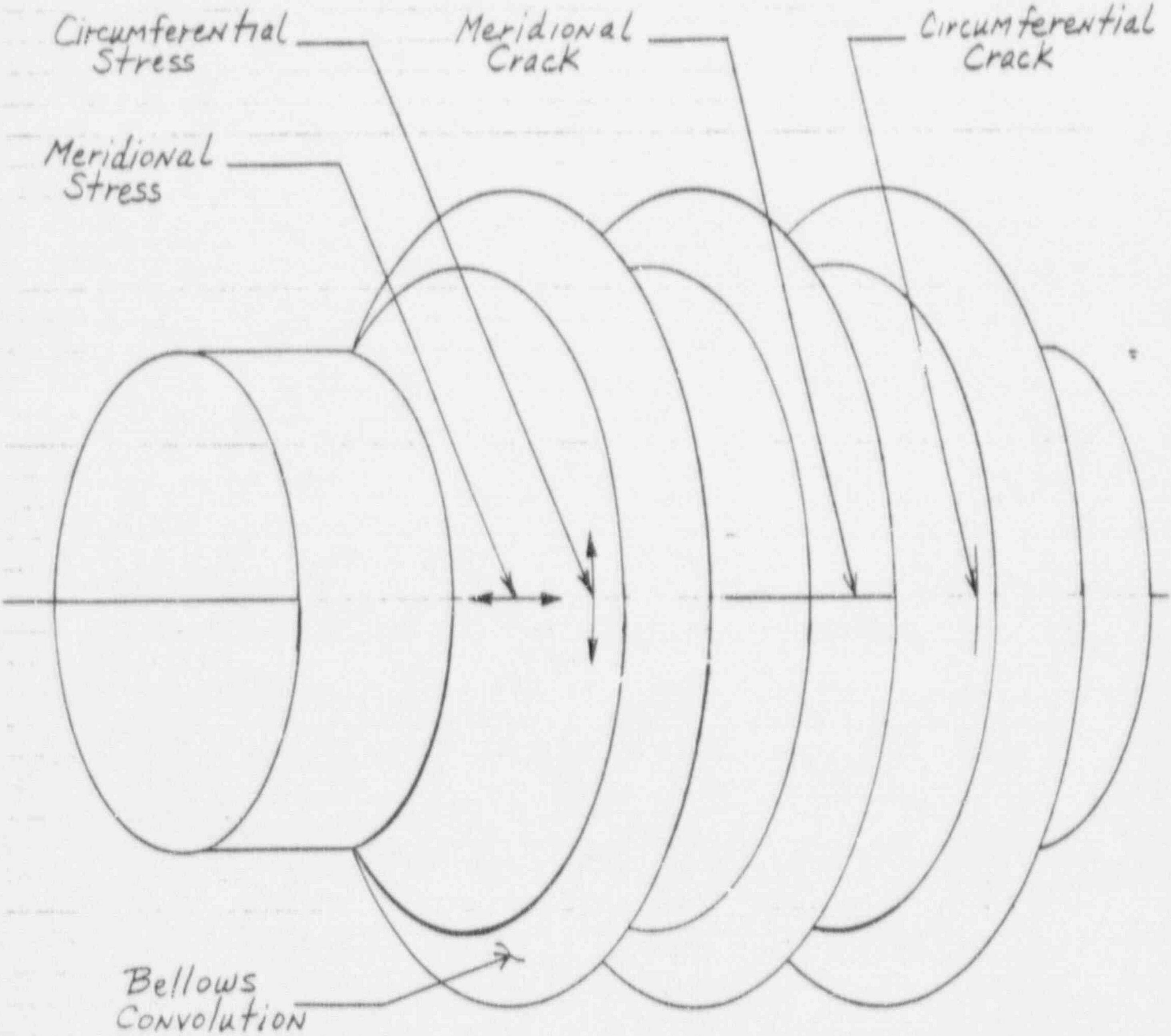
The form of stress corrosion cracking can be intergranular or transgranular and the cracking is difficult to detect. Despite the large amount of research which has been done, particularly on stainless steels, no agreed upon mechanism for transgranular stress corrosion cracking exists.

Based upon Appendix A to EPRI RP-5064S, a conservative value for stress corrosion crack propagation in 304 stainless steel due to chlorides would be 10^{-10} m/sec = 10^{-7} mm/sec. Data presented for sensitized 304 stainless steel in EPRI RP-2293-1 (not yet issued) shows propagation rates in the range of 10^{-8} to 10^{-7} mm/sec. The steel in the X25 bellows should not be sensitized since its design temperature is only 300°F.

Using this conservative crack propagation rate, the increase in crack length over a plant cycle can be calculated:

$$(10^{-10}\ \text{m/sec})(39.37\ \text{in./m})(3600\ \text{sec/hr})(24\ \text{hr/day})(365.25\ \text{day/yr}) \times (1.5\ \text{yr/plant cycle}) = 0.1864\ \text{inch/plant cycle}$$

This implies that a crack 1.7 inches long would grow to no more than about 1-7/8 inches over one plant cycle. Note that this calculation tacitly assumes the bellows is continuously loaded above the stress corrosion cracking threshold throughout the plant cycle.



Meridional and Circumferential Stress and Crack Directions

ENGINEERING DESIGN & ANALYSIS SERVICES

SMC O'DONNELL INC.
PITTSBURGH, PENNSYLVANIA

BY TAD DATE 3-11-91 SUBJECT

SHEET NO. i OF i

CHKD. BY ______ DATE ______

PROJ. NO. 2165

CALCULATIONS FOR
BELLOWS EXPANSION JOINT
DESIGN EVALUATION
DRYWELL PENETRATION X-25
QUAD CITIES NUCLEAR POWER STATION
UNIT 1

Critical crack length for meridional through crack:

For a through thickness crack of length 2a,

$$K_I = \sigma\sqrt{\pi a} \qquad \text{(Rolfe \& Barsom, figure 1.10)}$$

$$\therefore\ a = \frac{1}{\pi}\left(\frac{K_I}{\sigma}\right)^2$$

$$a = a_{cr} \text{ for } \sigma = \sigma_{max}$$

$$a_{cr} = \frac{1}{\pi}\left(\frac{K_I}{\sigma_{max}}\right)^2$$

For the 1.785" lateral displacement case $\sigma_{range} = 75\text{ ksi} > 2\sigma_y = 60\text{ ksi}$

After first half cycle, will be cycling between −37.5 ksi and +37.5 ksi

$$a_{cr} = \frac{1}{\pi}\left(\frac{105\text{ ksi}\sqrt{\text{in}}}{37.5\text{ ksi}}\right)^2 = 2.496 \text{ inches}$$

$$\boxed{\therefore\ l_{cr} = 4.991 \text{ inches}}$$

For the 1.0239 inch lateral displacement case $\sigma_{range} = 43\text{ ksi} < 2\sigma_y$

After first half cycle, will be cycling between −13 ksi and +30 ksi

$$a_{cr} = \frac{1}{\pi}\left(\frac{105\text{ ksi}\sqrt{\text{in}}}{30\text{ ksi}}\right)^2 = 3.899 \text{ inches}$$

$$\boxed{\therefore\ l_{cr} = 7.799 \text{ inches}}$$

Number of cycles for 1.7 inches long meridional through crack to grow to critical length:

For austenitic stainless steel,

$$\frac{da}{dN} = 3.0\times10^{-10}(\Delta K)^{3.25} \qquad \text{(Rolfe \& Barsom eqn 8.5)}$$

$$\Delta K = \Delta\sigma\sqrt{\pi a}$$

$$\frac{da}{dN} = 3.0\times10^{-10}(\Delta\sigma\sqrt{\pi a})^{3.25}$$

$$da/dN = 3.0\times10^{-10}(\Delta\sigma\sqrt{\pi})^{3.25}\,a^{1.625}$$

$$a^{-1.625}da = 3.0\times10^{-10}(\Delta\sigma\sqrt{\pi})^{3.25}\,dN$$

$$\int_{a_0}^{a_{cr}} a^{-1.625}da = 3.0\times10^{-10}(\Delta\sigma\sqrt{\pi})^{3.25}\int_0^N dN$$

$$\frac{a_{cr}^{-.625} - a_0^{-.625}}{-.625} = 3.0\times10^{-10}(\Delta\sigma\sqrt{\pi})^{3.25}\,N$$

$$N = [a_0^{-.625} - a_{cr}^{-.625}]\,\frac{1}{1.875\times10^{-10}(\Delta\sigma\sqrt{\pi})^{3.25}}$$

For the 1.785 inches lateral displacement case $\Delta\sigma = 75$ ksi

$$N = \frac{[a_0^{-.625} - a_{cr}^{-.625}]}{1.875\times10^{-10}(75\sqrt{\pi})^{3.25}} = \frac{a_0^{-.625} - a_{cr}^{-.625}}{1.4956\times10^{-3}}$$

$$N = 669\,[(0.85)^{-.625} - (2.496)^{-.625}]$$

N = 363 cycles

Suppose we add corrosion so $l_0 = 1.7 + 0.1864 = 1.8864$ inches

$$N = 669\,[(0.9432)^{-.625} - (2.496)^{-.625}]$$

N = 316 cycles

For the 1.0239 inch lateral displacement case $\Delta\sigma = 43$ ksi

$$N = \frac{a_0^{-.625} - a_{cr}^{-.625}}{1.875\times10^{-10}(43\sqrt{\pi})^{3.25}} = 4077\,[a_0^{-.625} - a_{cr}^{-.625}]$$

$$N = 4077\,[(0.85)^{-.625} - (3.899)^{-.625}]$$

N = 2771 cycles

Critical circumferential through crack length:

$$l_{cr} = \frac{2}{\pi}\left(\frac{K_I}{\sigma_{max}}\right)^2$$

For the 1.785 inches lateral displacement case $\sigma_{range} = 85\,ksi > 2\sigma_y$

After first half cycle, will be cycling between −42.5 ksi and +42.5 ksi

$$l_{cr} = \frac{2}{\pi}\left(\frac{105\,ksi\cdot\sqrt{in}}{42.5\,ksi}\right)^2$$

$$\boxed{l_{cr} = 3.886 \text{ inches}}$$

For the 1.0239 inch lateral displacement case $\sigma_{range} = 48.8\,ksi < 2\sigma_y$

After first half cycle, will be cycling between −18.8 ksi and +30 ksi

$$l_{cr} = \frac{2}{\pi}\left(\frac{105\,ksi\sqrt{in}}{30\,ksi}\right)^2$$

$$\boxed{l_{cr} = 7.799 \text{ inches}}$$

String of pinhole cracks:

$$K_I = F\left(\frac{2a}{d}, N\right)\sigma\sqrt{a\pi} \qquad \text{(Sih handbook page 2.2.5-3)}$$

where d is the pitch of the line of cracks

2a is the length of each crack

N is the number of cracks

$F(\frac{2a}{d}, N)$ is given by graphs for N = 3, 5, 7, 11 and ∞ on page 2.2.5-4

We were asked to assume 100 = N and 2a = 1/8 inch

$$d = \frac{\pi D}{100} = \frac{\pi(18\,in)}{100} = 0.5655 \text{ inch}$$

$$\frac{2a}{d} = \frac{.125\text{ inch}}{.5655\text{ inch}} = 0.221 \implies F\left(\frac{2a}{d}, N\right) = 1.02$$

[Note: In reality this pitch does not permit much crack growth. Using fewer holes in the analysis would leave a more realistic ligament, but would push $F(2a/d, N)$ closer to 1.00, which is the value for one crack.]

$$K_I \leq 1.02\,\sigma\sqrt{\pi a} \qquad \text{[but we will use =]}$$

$$l_{cr} = \frac{2}{\pi}\left(\frac{K_I}{1.02\,\sigma_{max}}\right)^2$$

For the 1.785 inches lateral displacement case

$$l_{cr} = \frac{2}{\pi}\left(\frac{105\,ksi\sqrt{in}}{1.02\,[42.5\,ksi]}\right)^2$$

$$l_{cr} = 3.735 \text{ inches} \qquad [< 3.886 \text{ inches for one crack}]$$

$$N = \frac{a_0^{-.625} - a_{cr}^{-.625}}{1.875\times10^{-10}\left(1.02\,\Delta\sigma\sqrt{\pi}\right)^{3.25}}$$

$$N = \frac{a_0^{-.625} - a_{cr}^{-.625}}{1.875\times10^{-10}\left(1.02\,[85]\sqrt{\pi}\right)^{3.25}} = 417\left[a_0^{-.625} - a_{cr}^{-.625}\right]$$

$$N = 417\left[(.0625)^{-.625} - (1.867)^{-.625}\right]$$

$$\boxed{N = 2077 \text{ cycles}}$$

For the 1.0239 inch lateral displacement case

$$l_{cr} = \frac{2}{\pi}\left(\frac{105\,ksi\sqrt{in}}{1.02\,[30\,ksi]}\right)^2$$

$$l_{cr} = 7.496 \text{ inches}$$

$$N = \frac{a_0^{-.625} - a_{cr}^{-.625}}{1.875\times10^{-10}\left(1.02\,[48.8]\sqrt{\pi}\right)^{3.25}} = 2534\left[a_0^{-.625} - a_{cr}^{-.625}\right]$$

$$N = 2534\left[(.0625)^{-.625} - (3.748)^{-.625}\right]$$

$$\boxed{N = 13225 \text{ cycles}}$$

Penetration No. X-25

Bellows Design Data:

Manufacturer	- Pathway
Type	- Universal Expansion Joint
Material	- SA-240, TP304
Outer Diameter	- 19 1/4"
Inner Diameter	- 17"
Number of Plies	- 2
Wall Thickness	- 0.040"
Number of Convolutions	- 10 per bellow

Design Movements:

- Axial - within tie-rod unit, assume 0"
- Lateral - 1.785"
- Angular - 0

Allowable Installation Misalignments (Non-cyclic):

- Axial - 0.25"
- Lateral - 0.125"
- Angular - 0

Design Pressure	- 65 psig
Design Temperature	- 300 °F
Operating Pressure	- 2 psig
Operating Temperature	- 150 °F
Local Leak Rate Test Pressure	- 48 psig
Integrated Leak Rate Test Pressure	- 65 psig

Cyclic Loading:

	Loading	No. Cycles
Design Pressure	- 65 psig	1
Local Leak Rate Test Pressure	-- 48 psig	20
Integrated Leak Rate Test Pressure	- 65 psig	20
Normal Operating Pressure	- ± 2 psig	4900
Bellows Movements:		4900

Axial - 0
Lateral - 1.66"
Angular - 0

Pressure / Temperature Transients:

	CASE NO.	1 (2)	2	3 (2)	4
	Drywell Pressure [psig]	62	0	56	0
	Drywell Temperature Change	221 °F	130 °F	221 °F	60 °F
Bellows Movements	Axial, X [inches]	0	0	0	0
	Lateral, Y (3) [inches]	1.785	1.0239	1.769	0.5399
	Angular, θ [degrees]	0	0	0	0
	Equivalent Axial Movement Range Per Convolution, e [in.]	0.0933	0.0535	0.0925	0.0282

NOTES:

1. Reference: Stress Report QCNPS-CBI Contract 9-6735, Volume A - Drywell
2. Penetrating pipe conditions:
   Pressure - 65 psig
   Temperature - 300 °F
3. The 1/8" allowable lateral movement due to misalignment at installation is included.

Design Evaluation

The design evaluations are performed by using the design equations presented in the Standards of The Expansion Joint Manufacturers Association, Inc. (EJMA), Fifth Edition, 1980. While the ASME Boiler & PV Code Section VIII - Div. 1, Appendix BB has bellows design equations that are very similar to EJMA's, it does not specifically address two-ply or multi-ply bellows, nor bellows design for lateral or angular movements.

A universal expansion joint is shown in Figure C5 on the following page. From Pathway Bellows, Inc. Drawing 8052,

$$C = 9"$$

$$L = 9" + 14" + 9" = 32"$$

The bellows convolution depth w, pitch q, thickness t, and tangent diameter d, are shown in Figure C16.

$$w = (O.D. - I.D.)/2 = (19\tfrac{1}{4}" - 17")/2$$

$$w = 1.125"$$

$$d = I.D. = 17"$$

$$q = \frac{C}{N} = \frac{9"}{10} = 0.9"$$

$$d_p = d + w = 17" + 1.125"$$

$$d_p = 18.125" = \text{pitch diameter of convolutions}$$

C-1.4.1 (continued)

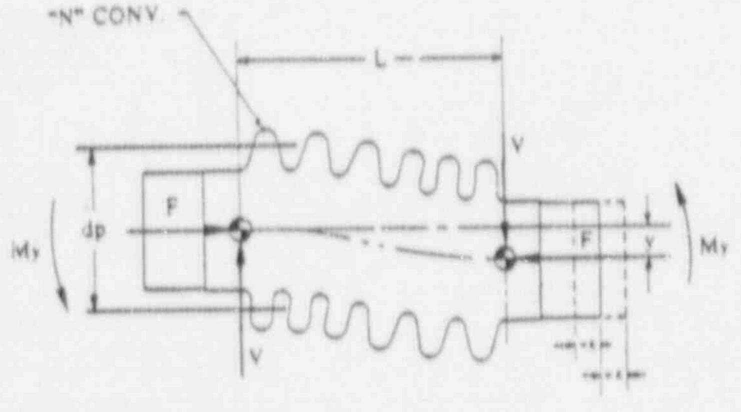


FIGURE C4

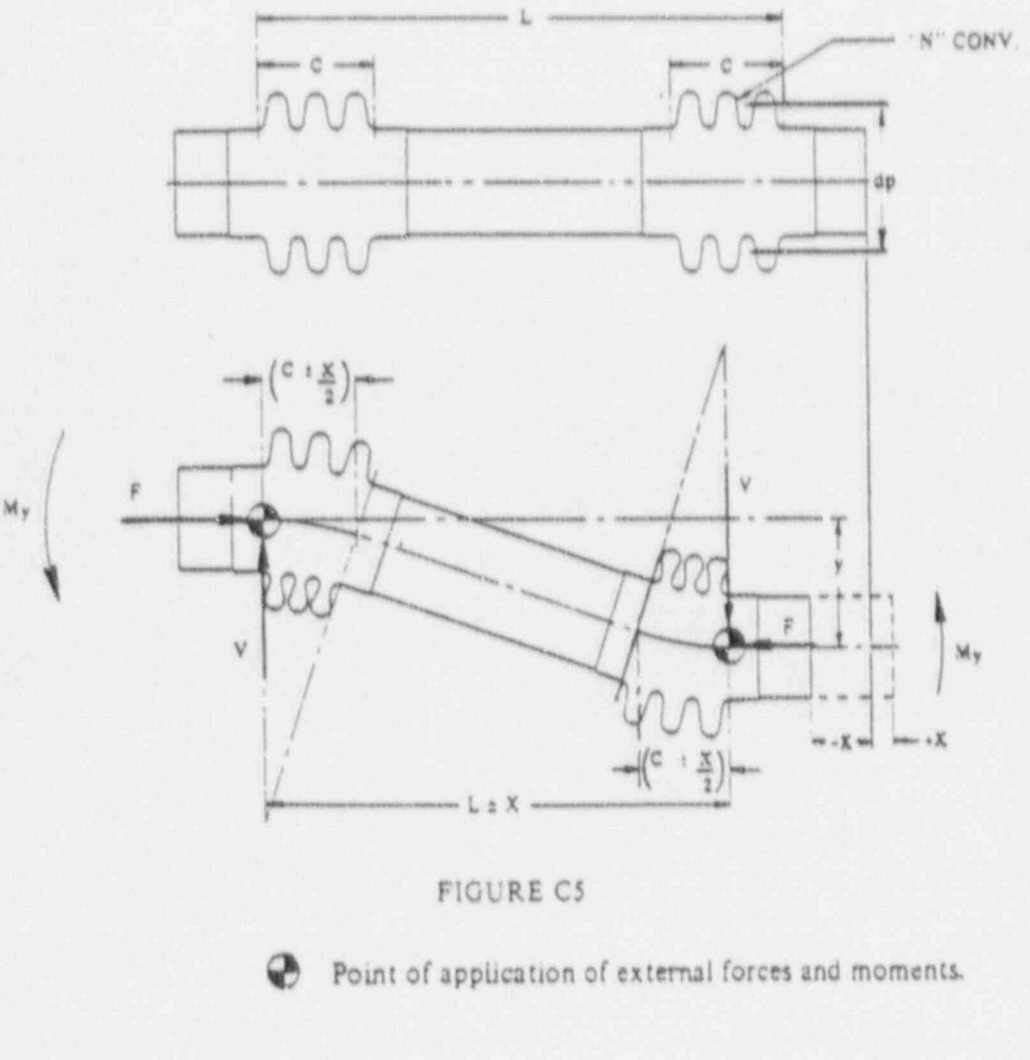
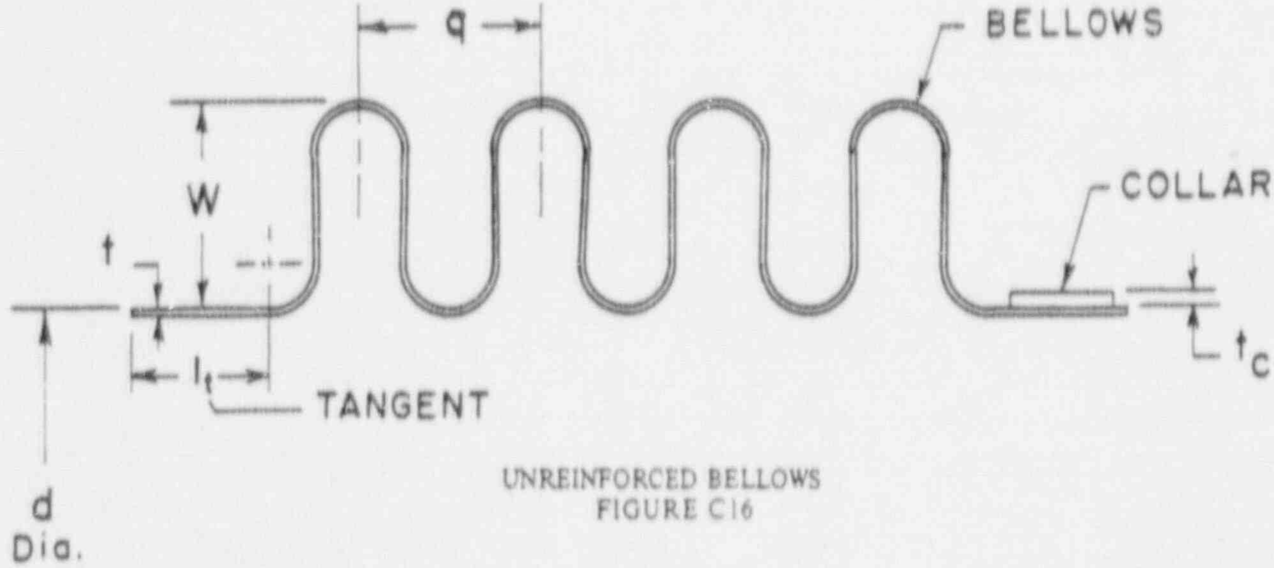
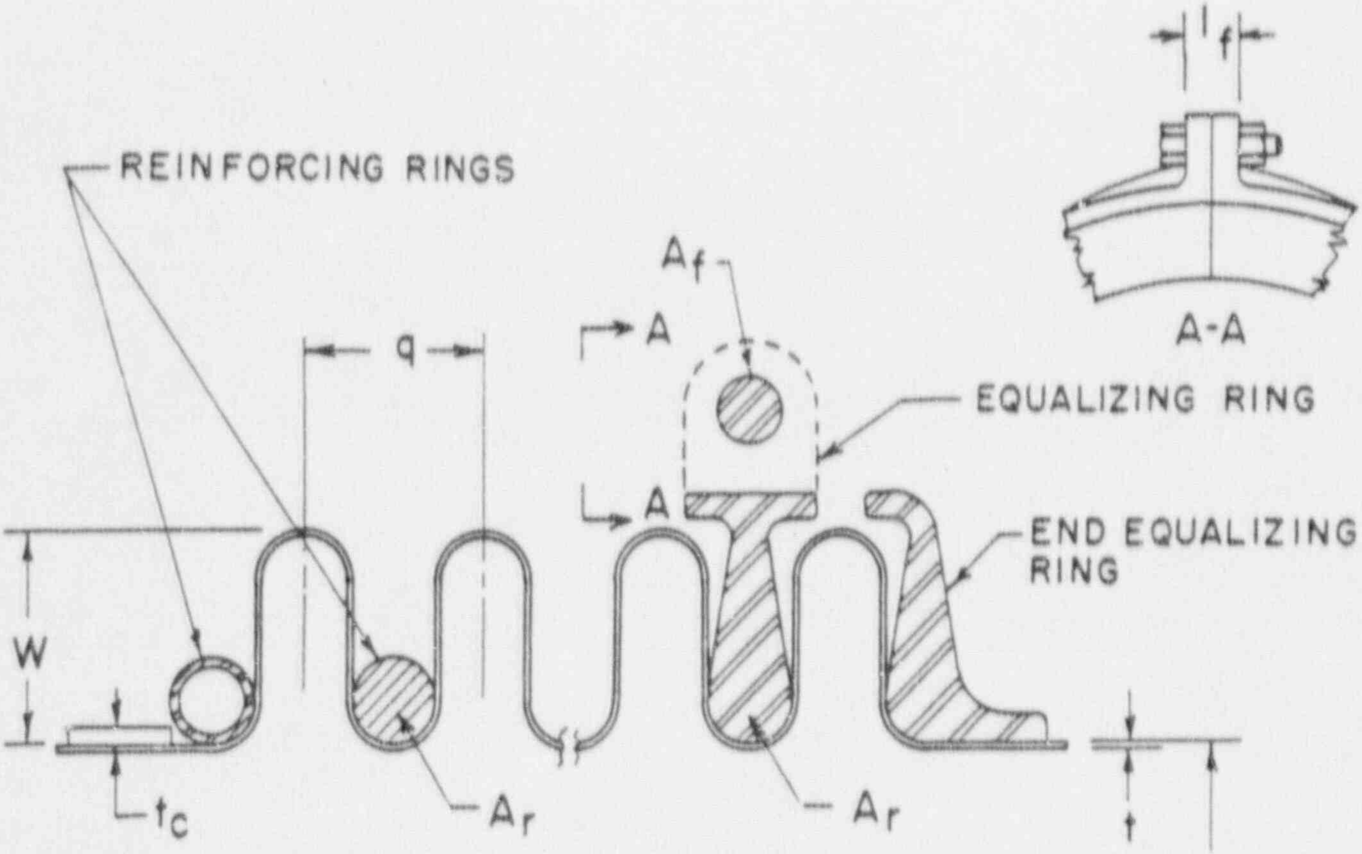


FIGURE C5

Point of application of external forces and moments.



UNREINFORCED BELLOWS
FIGURE C16



REINFORCED BELLOWS
FIGURE C17

Bellows Movements:

The bellows axial, lateral, and angular movements are the result of relative deflections between the drywell and penetration piping at the bellows assembly connection points. As shown in the table on page 2, bellows movements have been computed for four representative drywell pressure / temperature conditions.

Cases 1 and 3 bracket the accident conditions (LOCA, etc.), Case 4 represents the normal operating conditions (the pressure may actually be between -2 to +2 psig), while Case 2 is the conditions for an intermediate temperature transient.

The bellows design is evaluated for fatigue based on the conservative assumption that the accident conditions act for the full number of specified loading cycles, that is, by using the Case 1 condition for all cycles. The actual cycles will occur at conditions similar to those for Cases 2 and 4.

Cold Spring Movements:

An axial movement X of 1/4" due to misalignment at the time of installation is permitted by the specification. The bellows assembly tie rods eliminate any further axial movements. Hence, the axial movement per convolution is,

$$e_x = \frac{X}{2N} = \frac{0.25}{2(10)} = 0.0125'' \text{ compression or tension}$$

There are no angular movements θ specified.

$$e_\theta = \frac{\theta d_p}{2N} = 0$$

A lateral movement y of 1/8" is allowed by the specification for misalignment at the time of installation,

$$e_y = \frac{K d_p y}{2N(L - C \pm X/2)}$$ = equivalent axial movement per convolution due to lateral movement y

$$\frac{L}{2C} = \frac{32''}{2(9'')} = 1.78$$

$$K = \frac{3L^2 - 3CL}{3L^2 - 6CL + 4C^2} = \frac{3(32)^2 - 3(9)(32)}{3(32)^2 - 6(9)(32) + 4(9)^2}$$

$$K = 1.32$$

By assuming the axial movement X acts to compress the bellows, we find

$$e_y = \frac{1.32\,(18.125)(0.125)}{2(10)(32'' - 9'' - 0.25/2)}$$

$$e_y = 0.0065''$$

The effects of combined movements are calculated as follows:

$$e_c = e_y + e_\theta + e_x \text{ , compression}$$

$$e_c = 0.0065'' + 0 + 0.0125'' = 0.0190''$$

$$e_e = e_y + e_\theta - e_x \text{ , extension}$$

$$e_e = 0.0065'' + 0 - 0.0125'' = -0.0060''$$

Design Movements (Case 1):

$$X = 0$$

$$e_x = 0$$

$$\theta = 0$$

$$e_\theta = 0$$

$$y = 1.66'' \text{ (in same direction as cold spring)}$$

$$e_y = \frac{1.32(18.125)(1.66 + 0.125)}{2(10)(32 - 9 - 0.25/2)}$$

$$e_y = 0.0933''$$

Combined Operating Movements

$$e_c = 0.0933'' + 0 + 0 = 0.0933''$$

$$e_e = 0.0933'' + 0 - 0 = 0.0933''$$

Combined Cold Spring Plus Operating Movement Range

$$e_c \text{ (cold spring)} + e_e \text{ (operating)} = 0.0190'' + 0.0933'' = 0.112'' = e$$

$$e_e \text{ (cold spring)} + e_c \text{ (operating)} = -0.006'' + 0.0933'' = 0.0873''$$

Design Stresses

Bellows Circumferential Membrane Stress Due to Internal Pressure

$$S_2 = \frac{P d_p}{2 n t_p}\left(\frac{1}{0.571 + 2w/q}\right)$$

n = 2 plies

t = 0.040"

$$t_p = t\left(\frac{d}{d_p}\right)^{1/2} = 0.040\left(\frac{17}{18.125}\right)^{1/2} = 0.0387"$$

P = 65 psi

$$S_2 = \frac{65(18.125)}{2(2)(0.0387)}\left(\frac{1}{0.571 + 2(1.125)/0.9}\right)$$

S_2 = 2480 psi < S_A = 14,100 psi @ 300°F

Bellows Meridional Membrane Stress Due to Internal Pressure

$$S_3 = \frac{PW}{2 n t_p}$$

P = 65 psi

$$S_3 = \frac{65(1.125)}{2(2)(0.0387)}$$

S_3 = 472 psi < S_A = 14,100 psi @ 300°F

Local thinning of the bellows wall thickness due to corrosion has not been observed.

Bellows Meridional Bending Stress Due to Internal Pressure

$$S_4 = \frac{P}{2n}\left(\frac{w}{t_p}\right)^2 C_p$$

$C_p = 0.73$ from EJMA Figure C18 for

$$\frac{q}{2w} = \frac{0.9}{2(1.125)} = 0.4$$

$$\frac{q}{2.2\sqrt{d_p t_p}} = \frac{0.9}{2.2\sqrt{(18.125)(0.0387)}} = 0.488$$

$$S_4 = \frac{65}{2(2)}\left(\frac{1.125}{0.0387}\right)^2 (0.73)$$

$$S_4 = 10{,}000 \text{ psi}$$

$$0.35\, S_4 = 3500 \text{ psi} < S_A = 14{,}100 \text{ psi @ } 300^\circ F$$

Bellows Meridional Membrane Stress Due to Deflection

$$S_5 = \frac{E_b t_p^2 e}{2 w^3 C_f}$$

$C_f = 1.5$ from EJMA Figure C19

$E_b = 28.3 \times 10^6$ psi

$$S_5 = \frac{28.3 \times 10^6 (0.0387)^2 (0.112)}{2(1.125)^3(1.5)}$$

$$S_5 = 1110 \text{ psi}$$

Bellows Meridional Bending Stress Due to Deflection

$$S_6 = \frac{5 E_b t_p e}{3 w^2 C_d}$$

C_d = 1.6 from EJMA Figure C20

$$S_6 = \frac{5(28.3 \times 10^6)(0.0387)(0.112)}{3(1.125)^2(1.6)}$$

$$S_6 = 101,000 \text{ psi}$$

Total Meridional Stress Range:

$$S_t = 0.7(S_3 + S_4) + (S_5 + S_6)$$

$$S_t = 0.7(472\text{psi} + 10,000\text{psi}) + (1110\text{psi} + 101,000\text{psi})$$

$$S_t = 109,000 \text{ psi}$$

T_f = temperature correction factor for bellows fatigue life.

$$T_f = \left(\frac{S_u\,cold + S_u\,hot}{2 S_u\,cold}\right)$$ When cyclic movement occurs at varying temperatures due to thermal expansion.

S_u = ultimate tensile strength (minimum values are used)

S_u cold = 75,000 psi at 70°F (room temperature)

S_u hot = 61,000 psi at 300°F (accident temperature)

$$T_f = \frac{75,000 + 61,000}{2(75,000)} = 0.91$$

N_c = Number of cycles to failure

$$N_c = \left(\frac{1.86 \times 10^6 \, T_f}{S_t - 54{,}000} \right)^{3.4} \quad \text{for unreinfored bellows}$$

$$N_c = \left(\frac{1.86 \times 10^6 (0.91)}{109{,}000 - 54{,}000} \right)^{3.4}$$

$$N_c = 1.15 \times 10^5$$

Note that the actual stress range S_R for the lateral movement cycles should not include the stress range due to installation misalignments. Therefore, the deflection range is $e_y = 0.0933''$ and,

$$S_R = (S_5 + S_6)\frac{e_y}{e} = (1110 + 101{,}000)\frac{0.0933}{0.112}$$

$$S_R = 85000 \text{ psi}$$

This stress range will be used in the Fracture Mechanics Evaluation for critical size of circumferential cracks.

Limiting Design Internal Pressure P_s Based on Column Instability (Squirm) - Both Ends of Bellows are Ridgidly Supported:

$$P_s = \frac{0.3\pi \, f_{iu}}{N_T^2 \, q}$$

$$f_{iu} = 1.7 \frac{d_p E_b t_p^3 n}{W^3 C_f} = \text{bellows axial spring rate per convolution}$$

$$f_{iu} = 1.7 \frac{(18.125)(28.3 \times 10^6)(0.0387)^3 (2)}{(1.125)^3 (1.5)} = 47{,}300 \text{ lb/in}$$

$$P_s = \frac{0.3\pi (47{,}300)}{(20)^2 (0.9)}$$

$$P_s = 124 \text{ psi} > 65 \text{ psi}, \text{ OK}$$

Vibration :

The lowest natural frequency f_1 for a Universal expansion joint is for axial motion.

$$f_1 = 4.43\sqrt{\frac{K_{SR}}{W}}$$

$$K_{SR} = \frac{f_{iu}}{N} = \text{overall axial spring rate of one bellows}$$

$$K_{SR} = \frac{47{,}300}{10} = 4730 \text{ lbs/in}$$

W = weight of center spool pipe plus weight of one bellows

$$W = \frac{\pi}{4}(18^2-17^2)(14)(0.283)$$
$$+2\pi(10)(0.29)(0.040)\left[(19.25+17)\left(\frac{0.9}{2}\right)+\frac{1}{4}(19.25^2-17^2)\right]$$

$$W = 109 \text{ lbs} + 27 \text{ lbs}$$

$$W = 136 \text{ lbs}$$

$$f_1 = 4.43\sqrt{\frac{4730}{136}}$$

$$f_1 = 26.1 \text{ hz.}$$

All other natural frequencies for the Universal Expansion Joint, including lateral vibration modes, are at least a multiple higher than f_1.

At a natural frequency of 26.1 hz. the Universal Expansion Joint will be acted upon by little more than the acceleration applied to it by the Drywell

movements which will be essentially the zero period acceleration for the seismic zone. Loads acting on the Universal Expansion Joint due to axial seismic piping movements will be carried by the tie rods, while lateral seismic piping movements will be small and easily absorbed at low stress by the bellows.

For example, using a greatly exaggerated horizontal acceleration of 1g, a bellows convolution will deflect axially,

$$e_x = (1)(W)(1/f_{iu})$$

$$e_x = (1)(136)(1/47300) = 0.0029''$$

The bellows meridional bending stress for this deflection is only,

$$S_6 = \frac{5 E_b t_p e_x}{3 w^2 C_d} = \frac{5(28.3\times10^6)(0.0387)(0.0029)}{3(1.125)^2(1.6)}$$

$$S_6 = 2600\ psi$$

Total Circumferential Stress Range:

To evaluate growth rates for meridional cracks, the circumferential stresses must be known. The EJMA Standards base their design evaluations primarily on the meridional stresses because they are somewhat higher than the circumferential stresses. Therefore, stress values found by using the "Final Report on the Development of Analytical Techniques for Bellows and Diaphragm Design," AFRPL Report No. TR 68-22, March 1968 by T.M. Trainer, et. al., are used to supplement the EJMA stress values.

The bellows circumferential membrane stress due to internal pressure taken by one ply, $S_2 = 4960$ psi, is found by using the EJMA Standards.

The bellows circumferential membrane stress due to the 1.66 inch cyclic lateral movement is found by using the appropriate figure in the above reference as follows:

$$\sigma_{sm} = \frac{e_y E_b}{100\, q} C_5$$

$$\sigma_{sm} = \frac{0.0933(28.3 \times 10^6)}{100(0.9)} (1.32)$$

$$\sigma_{sm} = 38{,}700 \text{ psi}$$

The bellows circumferential bending stresses due to internal pressure taken by one ply and lateral movement are simply Poisson's ratio ($\nu = 0.3$) times the corresponding meridional bending stresses:

$$\sigma_b = \nu n S_4 = 0.3(2)(10{,}000) = 6000 \text{ psi}$$

$$\sigma_d = \nu S_6 = 0.3(101{,}000)\frac{0.0933''}{0.112''} = 25{,}200 \text{ psi}$$

This results from the fact that the bellows is a shell of revolution, for which rotations in meridional sections are suppressed by the symmetry of the shell. Since the bellows shell cannot bend freely in this plane, a constraining Poisson's moment occurs.

The total circumferential stress range is

$$S_{tc} = nS_2 + \sigma_{sm} + \sigma_b + \sigma_d$$

$$S_{tc} = 2(2480) + 38{,}700 + 6000 + 25{,}200$$

$$S_{tc} \quad 75{,}000 \text{ psi}$$

This stress range will be used in the Fracture Mechanics Evaluation for growth rates of meridional cracks.