APPENDIX 3G

CRITERIA FOR BUCKLING EVALUATION OF CONTAINMENT VESSEL

[This appendix provides criteria for evaluation of the steel containment vessel for local buckling. The design of the containment vessel against buckling is based on the requirements of the ASME Code, Section III, Subsection NE. Methodology is provided for determining the structural adequacy against buckling of containment vessel components such as ellipsoidal heads, cylindrical shell, and equipment hatch covers. The criteria are based on the rules specified in ASME Code Case N-284, Rev 0 with supplemental requirements where the criteria in Revision 0 are insufficient.

The buckling capacity of the shell is based on linear bifurcation (classical) analyses reduced by capacity reduction factors which account for the effects of imperfections and nonlinearity in geometry and boundary conditions and by plasticity reduction factors which account for nonlinearity in material properties. The criteria are expressed in terms of allowable stresses. The allowable stress is calculated as the theoretical elastic instability stress multiplied by a capacity reduction factor and plasticity reduction factor and divided by the factor of safety. The stresses calculated by elastic analyses and these allowable stresses are then used in interaction relationships.

*The governing factor in the buckling analysis is the compressive membrane stress zones arising from the response of the containment vessel to the applied loadings. The procedures of these criteria call for linear shell analyses. The internal stress field which controls the buckling of a cylindrical, spherical, or ellipsoidal shell consists of the meridional (longitudinal) membrane, circumferential membrane, and in-plane shear stresses. These stresses may exist singly or in combination, depending on the applied loading. Only these three stress components are considered in the buckling evaluation.]**

3G.1 Notation

[E = *modulus of elasticity, psi*]*

[FS = *factor of safety*]*

[L = *subscript for local buckling*]*

[l_φ, l_θ = *distance between lines of support in* φ *and* θ *direction, respectively, in.*]*

[M_φ , M_θ = $l_\varphi / \sqrt{Rt}$, $l_\theta / \sqrt{Rt}$, *respectively*]*

[M = smaller of M_φ and M_θ]*

[R = *shell radius, in.*]*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

[R_1, R_2 = *effective stress radius for ellipsoidal shells in the* φ *and* θ *direction, respectively, in.*]*

[t = *shell thickness, in.*]*

[φ, θ, $\varphi\theta$ = *corresponding to meridional, circumferential, and in-plane direction, respectively*]*

[σ_e = *theoretical elastic instability stresses, psi*]*

[σ_y = *yield stress, psi*]*

3G.2 Factors of Safety

[*The factor of safety (FS) is applied to buckling stress values that are determined by classical (linear) analysis and have been reduced by capacity reduction factors determined from lower bound values of test data.*

- *Design Conditions and Level A and B Service Limits: FS = 2.0*
- *Level C Service Limits: FS = 1.67*
- *Level D Service Limits: FS = 1.34*]*

3G.3 Capacity Reduction Factors

[*The capacity as determined by linear bifurcation (classical) analysis is not attained for actual shells. The reduction in capacity due to imperfections and nonlinearity in geometry and boundary conditions is provided through the use of capacity reduction factors,* α, *given below for shells which meet the tolerances of NE-4220.*]*

3G.3.1 Cylindrical Shells

3G.3.1.1 Axial Compression

[*Use the larger of the values determined from (1) and (2).*

(1a) $\alpha_{\varphi L} = 0.207$ *for* $R/t \geq 600$

(1b) Smaller of the values *for* $R/t < 600$

$\alpha_{\varphi L} = 1.52 - 0.473 \log_{10}(R/t)$, *and*

$\alpha_{\varphi L} = 300\, \sigma_y / E - 0.033$

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

(2) $\alpha_{\varphi L} = 0.627$ *if* $M_\varphi < 1.5$
$\alpha_{\varphi L} = 0.837 - 0.14\ M_\varphi$ *if* $1.5 \leq M_\varphi < 1.73$
$\alpha_{\varphi L} = 0.826 / (M_\varphi)^{0.6}$ *if* $1.73 \leq M_\varphi < 10$
$\alpha_{\varphi L} = 0.207$ *if* $M_\varphi \geq 10$]*

3G.3.1.2 Hoop Compression

[$\alpha_{\theta L} = 0.8$]*

3G.3.1.3 Shear

[$\alpha_{\theta\varphi L} = 0.8$ *if* $R/t \leq 250$
$\alpha_{\theta\varphi L} = 1.323 - 0.218\ \log_{10}(R/t)$ *if* $250 < R/t < 1000$]*

3G.3.2 Spherical Shells

[*The length* l_φ *or* l_θ *used in calculating M is equal to the diameter of the largest circle which can be inscribed within the lines of support. The length is measured along the arc.*]*

3G.3.2.1 Uniaxial Compression

[$\alpha_{\varphi L} = \alpha_{\theta L} = \alpha_{1L} = \alpha_{2L} / 0.6$, *but not to exceed 0.75. See subsection 3G.3.2.2 for* α_{2L}.]*

3G.3.2.2 Equal Biaxial Compression

[$\alpha_{\varphi L} = \alpha_{\theta L} = \alpha_{2L}$

$\alpha_{2L} = 0.627$ *if* $M < 1.5$
$\alpha_{2L} = 0.837 - 0.14\ M$ *if* $1.5 \leq M < 1.73$
$\alpha_{2L} = 0.826 / (M)^{0.6}$ *if* $1.73 \leq M < 23.6$
$\alpha_{2L} = 0.124$ *if* $M \geq 23.6$]*

3G.3.2.3 Unequal Biaxial Compression

[*Use* α_{1L} *and* α_{2L} *in accordance with subsection 3G.3.2.1 and subsection 3G.3.2.2.*]*

3G.3.2.4 Shear

[*Buckling evaluation is made using principal stresses.*]*

3G.3.3 Ellipsoidal Shells

[*Use* α_{1L} *and* α_{2L} *given for spherical shells in subsection 3G.3.2.1 and subsection 3G.3.2.2.*]*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

3G.4 Plasticity Reduction Factors

[The elastic buckling stresses for fabricated shells are given by the product of the classical buckling stresses and the capacity reduction factors, i. e., $\sigma_e \times \alpha$*. When these values exceed the proportional limit of the fabricated material, plasticity reduction factors,* η*, are used to account for the non-linear material properties. The inelastic buckling stresses for fabricated shells are given by* $\eta \times \sigma_e \times \alpha$*.]**

3G.4.1 Cylindrical Shells

[Let $\Delta = [\ \alpha_{iL} \times \sigma_{ieL}\ ] / \sigma_y$*,*

where:

$i = \varphi, \theta,$ *or* $\varphi\theta$*]**

3G.4.1.1 Axial Compression

[$\eta_\varphi = 1.0$	if $\Delta \leq 0.55$
$\eta_\varphi = [\ 0.45 / \Delta\ ] + 0.18$	if $0.55 < \Delta \leq 1.6$
$\eta_\varphi = 1.31 / [\ 1 + 1.15 \times \Delta\ ]$	if $1.6 < \Delta < 6.25$
$\eta_\varphi = 1 / \Delta$	if $\Delta \geq 6.25$]*

3G.4.1.2 Hoop Compression

[$\eta_\theta = 1.0$	if $\Delta \leq 0.67$
$\eta_\theta = 2.53 / [\ 1 + 2.29 \times \Delta]$	if $0.67 < \Delta < 4.2$
$\eta_\theta = 1 / \Delta$	if $\Delta \geq 4.2$]*

3G.4.1.3 Shear

[$\eta_{\varphi\theta} = 1.0$	if $\Delta \leq 0.48$
$\eta_{\varphi\theta} = [\ 0.43 / \Delta\ ] + 0.1$	if $0.48 < \Delta < 1.7$
$\eta_{\varphi\theta} = 0.6 / \Delta$	if $\Delta \geq 1.7$]*

3G.4.2 Spherical Shells

3G.4.2.1 Meridional Compression and/or Hoop Compression

*[Use the values given in subsection 3G.4.1.1.]**

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

3G.4.3 Ellipsoidal Shells

3G.4.3.1 Meridional Compression and/or Hoop Compression

[*Use the values given in subsection 3G.4.1.1.*]*

3G.5 Theoretical Buckling Values

[*The buckling stresses given by the following equations correspond to the minimum values determined from theoretical equations for shells with classical simple support boundary conditions under uniform stress fields.*]*

3G.5.1 Cylindrical Shells

3G.5.1.1 Axial Compression

[$\sigma_{\varphi eL} = C_\varphi \times E \times t/R$

$C_\varphi = 0.630$	if $M_\varphi \leq 1.5$
$C_\varphi = 0.904 / [M_\varphi]^2 + 0.1013 \times M_\varphi^2$	if $1.5 < M_\varphi < 1.73$
$C_\varphi = 0.605$	if $M_\varphi \geq 1.73$]*

3G.5.1.2 External Pressure

[*a.* ***No End Pressure*** ($\sigma_\varphi = 0$)

$\sigma_{\theta eL} = \sigma_{reL} = C_{\theta r} \times E \times t/R$

$C_{\theta r} = 1.616$	if $M_\varphi \leq 1.5$
$C_{\theta r} = 2.41 / [M_\varphi^{1.49} - 0.338]$	if $1.5 < M_\varphi < 3.0$
$C_{\theta r} = 0.92 / [M_\varphi - 1.17]$	if $3.0 \leq M_\varphi < 1.65R/t$
$C_{\theta r} = 0.275t/R + [2.1/M_\varphi^4] \times (R/t)^3$	if $M_\varphi \geq 1.65R/t$

b. End Pressure Included ($\sigma_\varphi = 0.5\ \sigma_\theta$)

$\sigma_{\theta eL} = \sigma_{heL} = C_{\theta h} \times E \times t / R$

$C_{\theta h} = 0.988$	if $M_\varphi \leq 1.5$
$C_{\theta h} = 1.08 / [M_\varphi^{1.07} - 0.45]$	if $1.5 < M_\varphi < 3.5$
$C_{\theta h} = 0.92 / [M_\varphi - 0.636]$	if $3.5 \leq M_\varphi < 1.65R/t$
$C_{\theta h} = 0.275t/R + [2.1 / M_\varphi^4] \times (R/t)^3$	if $M_\varphi \geq 1.65R/t$]*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

3G.5.1.3 Shear

[$\sigma_{\varphi\theta eL} = C_{\varphi\theta} \times E \times t/R$

$C_{\varphi\theta} = 2.227$ *if* $M_\varphi \le 1.5$
$C_{\varphi\theta} = [4.82 / M_\varphi^{\,2}] \times (1+0.0239\, M_\varphi^{\,3})^{1/2}$ *if* $1.5 < M_\varphi < 26$
$C_{\varphi\theta} = 0.746 / [M_\varphi^{\,1/2}]$ *if* $26 \le M_\varphi < 8.69R/t$
$C_{\varphi\theta} = 0.253 \times (t/R)^{1/2}$ *if* $M_\varphi \ge 8.69R/t$]*

3G.5.2 Spherical Shells

3G.5.2.1 Equal Biaxial Compression

[$\sigma_{\varphi eL} = \sigma_{\theta eL} = C \times E \times t/R$

$C = 0.630$ *if* $M \le 1.5$
$C = 0.904 / [M]^2 + 0.1013 \times M^2$ *if* $1.5 < M < 1.73$
$C = 0.605$ *if* $M \ge 1.73$]*

3G.5.2.2 Unequal Biaxial Compression

[*See subsection 3G.6.1.2 for evaluation of unequal biaxial compression.*]*

3G.5.2.3 Shear

[*When shear is present, the principal stresses are calculated and substituted for* σ_φ *and* σ_θ *in the buckling equations.*]*

3G.5.3 Ellipsoidal Shells

[*Ellipsoidal shells are analyzed as equivalent spheres.*]*

3G.6 Interaction Equations for Local Buckling

[*This section identifies interaction equations used to evaluate the local buckling capacity of the shell. The form of such interaction relationships depends on whether the critical stresses are in the elastic or inelastic range. If any of the uniaxial critical stress values exceed the proportional limit of the fabricated material, the inelastic interaction relationships of subsection 3G.6.2 should be satisfied, in addition to the elastic interaction relationships of subsection 3G.6.1. If the calculated meridional or hoop stress is tension, it should be assumed zero for the interaction evaluation.*]*

3G.6.1 Elastic Buckling

[*The relationships in the following paragraphs must be satisfied.*]*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

3G.6.1.1 Cylindrical Shells

[The allowable stresses for the special load cases of axial (meridional) compression alone, hydrostatic external pressure, radial external pressure and in-plane shear alone are given by:

$\sigma_{xa} = [\alpha_{\varphi L} \times \sigma_{\varphi eL}] / FS,$

$\sigma_{ha} = [\alpha_{\theta L} \times \sigma_{heL}] / FS,$

$\sigma_{ra} = [\alpha_{\theta L} \times \sigma_{reL}] / FS,$ *and*

$\sigma_{\tau a} = [\alpha_{\varphi\theta} \times \sigma_{\varphi\theta eL}] / FS$

These stresses are used in the interaction equations which follow for combined stress states.

a. Axial Compression Plus Hoop Compression $(\sigma_\varphi / \sigma_\theta < 0.5)$

No interaction check is required if $\sigma_\theta < \sigma_{ha}$.

$\sigma_\theta / [\ \sigma_{ra} - 2\ \sigma_\varphi \times \{ (\ \sigma_{ra} / \sigma_{ha}\ ) - 1 \}\ ] \leq 1.0$

b. Axial Compression Plus Hoop Compression $(\sigma_\varphi / \sigma_\theta \geq 0.5)$

No interaction check is required if $\sigma_\varphi < 0.5 \times \sigma_{ha}$.

$[\ \sigma_\varphi - 0.5 \times \sigma_{ha}\ ] / [\ \sigma_{xa} - 0.5 \times \sigma_{ha}\ ] + (\sigma_\theta / \sigma_{ha}\ )^2 \leq 1.0$

c. Axial Compression Plus In-Plane Shear

$[\ \sigma_\varphi] / [\ \sigma_{xa}] + (\ \sigma_{\varphi\theta} / \sigma_{\tau a}\ )^2 \leq 1.0$

d. Hoop Compression Plus In-Plane Shear

$[\ \sigma_\theta] / [\ \sigma_{ra}] + (\ \sigma_{\varphi\theta} / \sigma_{\tau a}\ )^2 \leq 1.0$

e. Axial Compression Plus Hoop Compression Plus In-Plane Shear

For a given shear ratio $(\sigma_{\varphi\theta} / \sigma_{\tau a}\ )$ *determine the value,* $K_s = 1 - (\sigma_{\varphi\theta} / \sigma_{\tau a}\ )^2$, *and substitute the values of* $K_s\sigma_{xa}$, $K_s\sigma_{ra}$, *and* $K_s\sigma_{ha}$ *for* σ_{xa}, σ_{ra}, *and* σ_{ha}, *respectively, in the equations given in (a) or (b) above.]**

3G.6.1.2 Spherical Shells

[The allowable stresses for the special load cases of uniaxial compression and uniform external pressure are given by the equations which follow and are used in the interaction

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equation for other biaxial compression stress states. If one stress component is in tension, the tensile stress may be set to zero and the shell considered as a uniaxial compression case.

$\sigma_{1a} = [\alpha_{1L} \times \sigma_{\varphi eL}] / FS$, *and*

$\sigma_{2a} = [\alpha_{2L} \times \sigma_{\varphi eL}] / FS$

When $\sigma_{\varphi\theta} \neq 0$, *determine the principal stresses corresponding to stress components and substitute for* σ_φ *and* σ_θ *in the expressions below for* σ_1 *and* σ_2,

where:

σ_1 = *larger compression stress of* σ_φ *and* σ_θ

σ_2 = *smaller compression stress of* σ_φ *and* σ_θ

a. Uniaxial Compression

$\sigma_1 / \sigma_{1a} \leq 1.0$

b. Biaxial Compression

$(\sigma_1 - \sigma_2) / [\sigma_{1a}] + \sigma_2 / \sigma_{2a} \leq 1.0$

*The acceptance criteria identified in **a.** and **b.** above are used in the design of the containment vessel documented in subsection 3.8.2. The design resulting from **a.** and **b.** above has been demonstrated to be adequate for the containment vessel certified design based in part on an independent confirmatory analysis by the NRC staff. Unrestricted use of this equation is not considered acceptable without additional technical justification. Where additional design evaluations are performed by the Combined License applicant, non-linear buckling analyses shall demonstrate a factor of safety against buckling in accordance with subsection 3G.2. The factor of safety against buckling (ratio of the calculated critical buckling stresses to the membrane compressive stresses due to the specified design loads and load combinations) may be calculated by numerical analyses such as BOSOR-5, ANSYS, or ABAQUS of a portion of the containment vessel with appropriate boundary conditions. The analyses shall consider the effect of geometric imperfections and plasticity.*]*

3G.6.1.3 Ellipsoidal Shells

[*The allowable stresses for the special stress states of uniaxial compression and equal biaxial compression are given by the equations which follow and these values are used in the interaction equation for other stress states.*

$\sigma_{1a} = [\alpha_{1L} \times \sigma_{1eL}] / FS$, *and*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

$\sigma_{2a} = [\alpha_{2L} \times \sigma_{2eL}] / FS$

where:

α_{1L} *and* α_{2L} *are defined in subsection 3G.3.2.1.*

Calculate σ_{1eL} *and* σ_{2eL} *from the following procedure.* $\sigma_{\varphi eL}$ *is defined in subsection 3G.5.2.1.*

$\sigma_{1eL} = \sigma_{\varphi eL}$ *= theoretical buckling stress for sphere under equal biaxial stress based on R associated with* σ_1. $R = R_1$ *if* $\sigma_1 = \sigma_\theta$ *and* $R = R_2$ *if* $\sigma_1 = \sigma_\varphi$.

$\sigma_{2eL} = \sigma_{\varphi eL}$ *= theoretical buckling stress for sphere under equal biaxial stress based on R associated with* σ_2. $R = R_1$ *if* $\sigma_2 = \sigma_\theta$ *and* $R = R_2$ *if* $\sigma_2 = \sigma_\varphi$.

When $\sigma_{\varphi\theta} \neq 0$*, determine the principal stresses corresponding to stress components and substitute for* σ_φ *and* σ_θ *in the expressions given in subsection 3G.6.1.2. Also determine radii* R_1 *and* R_2 *which correspond to the principal stress directions.*

a. Uniaxial Compression

See subsection 3G.6.1.2 (a).

b. Biaxial Compression

See subsection 3G.6.1.2 (b).]*

3G.6.2 Inelastic Buckling

[*The relationships in the following paragraphs must also be satisfied when any of the values of* $\eta < 1$. *No interaction equations are given for meridional compression plus hoop compression because it is conservative to ignore interaction of the two stress components when buckling is inelastic.*]*

3G.6.2.1 Cylindrical Shells

[*The allowable stresses for the special stress states of axial (meridional) compression alone, radial external pressure, and in-plane shear alone are given by:*

$\sigma_{xc} = \eta_\varphi \times \sigma_{xa}$, $\sigma_{rc} = \eta_\theta \times \sigma_{ra}$, *and* $\sigma_{\tau c} = \eta_{\varphi\theta} \times \sigma_{\tau a}$

where:

η *is defined in subsection 3G.4.1 and,*

σ_{xa}, σ_{ra}, *and* $\sigma_{\tau a}$ *are defined in subsection 3G.6.1.1.*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.

a. Axial Compression or Hoop Compression

$\sigma_{\varphi} / \sigma_{xc} \leq 1.0$ *or* $\sigma_{\theta} / \sigma_{rc} \leq 1.0$

b. Axial Compression Plus In-Plane Shear

$[\ \sigma_{\varphi}\ ] / [\ \sigma_{xc}\ ] + (\ \sigma_{\varphi\theta} / \sigma_{\tau c}\ )^2 \leq 1.0$

c. Hoop Compression Plus In-Plane Shear

$[\ \sigma_{\theta}] / [\ \sigma_{rc}] + (\ \sigma_{\varphi\theta} / \sigma_{\tau c}\ )^2 \leq 1.0$]*

3G.6.2.2 Spherical Shells

[*a. Uniaxial or Biaxial Compression*

$\sigma_1 / \sigma_{1c} \leq 1.0$

where:

$\sigma_{1c} = \eta_{\varphi} \times \sigma_{1a}$ *and* η_{φ} *corresponds to stress* $\sigma_{1a} \times FS$.

See subsection 3G.4.2 for η_{φ} *and subsection 3G.6.1.2 for* σ_1 *and* σ_{1a}.]*

3G.6.2.3 Ellipsoidal Shells

[$\sigma_{1c} = \eta_1 \times \sigma_{1a}$ *or* $\sigma_{2c} = \eta_2 \times \sigma_{2a}$

where:

η_1 *corresponds to stress* $\sigma_{1a} \times FS$ *and* η_2 *corresponds to stress* $\sigma_{2a} \times FS$.

See subsection 3G.4.3 for η_1 *and* η_2 *and subsection 3G.6.1.3 for* σ_1, σ_{1a}, σ_2, *and* σ_{2a}.

a. Uniaxial Compression Plus In-Plane Shear

$\sigma_1 / \sigma_{1c} \leq 1.0$

b. Biaxial Compression Plus In-Plane Shear

$\sigma_1 / \sigma_{1c} \leq 1.0$ *and* $\sigma_2 / \sigma_{2c} \leq 1.0$ *(both equations must be satisfied)*]*

*NRC Staff approval is required prior to implementing a change in this information; see DCD Introduction Section 3.5.