APPENDIX D
Application of Regulatory Guide 7.6 for NNSA Packages (Structural Design Criteria)

As discussed in Section 2.4, RG 7.6[D-1] was developed in the late 1970s specifically for spent nuclear fuel casks. It is based on the 1977 version of the ASME BPVC, Section III, Division 1, Subsection NB[D-2] for Class 1 components. Therefore, much of the guidance in RG 7.6 is based on the “design by analysis” and stress categorization methods outlined in Article NB-3000 for Class 1 components. At that time, the predominate method of analysis was classical linear elastic methods.

RG 7.6 has not changed since its issuance in 1978, while the ASME BPVC and analytical methods have evolved over time. As a result, the NNSA guidance in Section 2.5 suggests that the current version of the ASME BPVC, Section III, Division 1, Subsection NB[D-3] be used, along with the appropriate requirements from RG 7.6 that are specific to packaging. The basis for this is that the packaging performance tests and the failure modes addressed by RG 7.6 have not changed substantially. The appropriate criteria that should be considered are those outlined in RG 7.6 Regulatory Positions 3, 4, 6, and 7. It should be recognized that these criteria are based on linear elastic methods and should be applied only to the containment system. Other appropriate non-linear methods can be applied to other components, such as the impact limiters. Also, since the ASME BPVC “design by analysis” method is based on the Maximum Shear Stress Theory of Failure, the stress intensity, which is the difference between the maximum and minimum principal stresses on the section being evaluated, must be evaluated. In using the guidance provided in Section 2.5 and RG 7.6, it should be recognized that HAC performance test evaluations may use the criteria specified in ASME BPVC, Section III, Division 1, Appendices,[D-4] Appendix F for Category I content package containment systems. Appendix F provides acceptance criteria for both elastic system analysis and plastic system analysis in Section F-1330 and Section F-1340, respectively. Both sections define acceptance criteria for Level D Service Limits for components designed in accordance with Subsection NB. Section F-1341 (Acceptance Criteria for Plastic System Analysis) allows the use of any one of the following structural acceptance criteria for demonstrating the acceptability of components:

1. Elastic analysis (F-1341.1).
2. Plastic analysis (F-1341.2).
3. Collapse load analysis (F-1341.3).
4. Plastic instability analysis (F-1341.4).
5. Interaction analysis (F-1341.5).

However, F-1340 states that these acceptance criteria may be applied provided that system analysis considers the effects of the material's non-linear behavior. These criteria are also subject to the restrictions in F-1322. In both sections, the stresses must be classified as described in Table NB-3217-1.

Since the development of ASME BPVC and RG 7.6, the use of computer codes has become commonplace for assessing the performance of containment systems. However, the "design by analysis" and stress classification methods specified in the current ASME BPVC and RG 7.6 are not easily applied in dynamic finite element analysis (FEA) evaluations of the containment system under regulatory performance tests. In the past, most containment system evaluations were based on quasi-static classical linear elastic methods or quasi-static methods using static FEA loading evaluation methods, which are relatively easily applied to ASME BPVC "design by analysis" and stress categorization methods. With the advent of dynamic FEA methods (e.g., ABAQUS/Explicit and LS-DYNA-3D) for assessing impact loads, the application of the ASME BPVC "design by analysis" and stress classification methods have become more difficult. There are two main problems with adapting the ASME BPVC "design by analysis" methods to dynamic FEA methods for assessing impact loads, as discussed below.

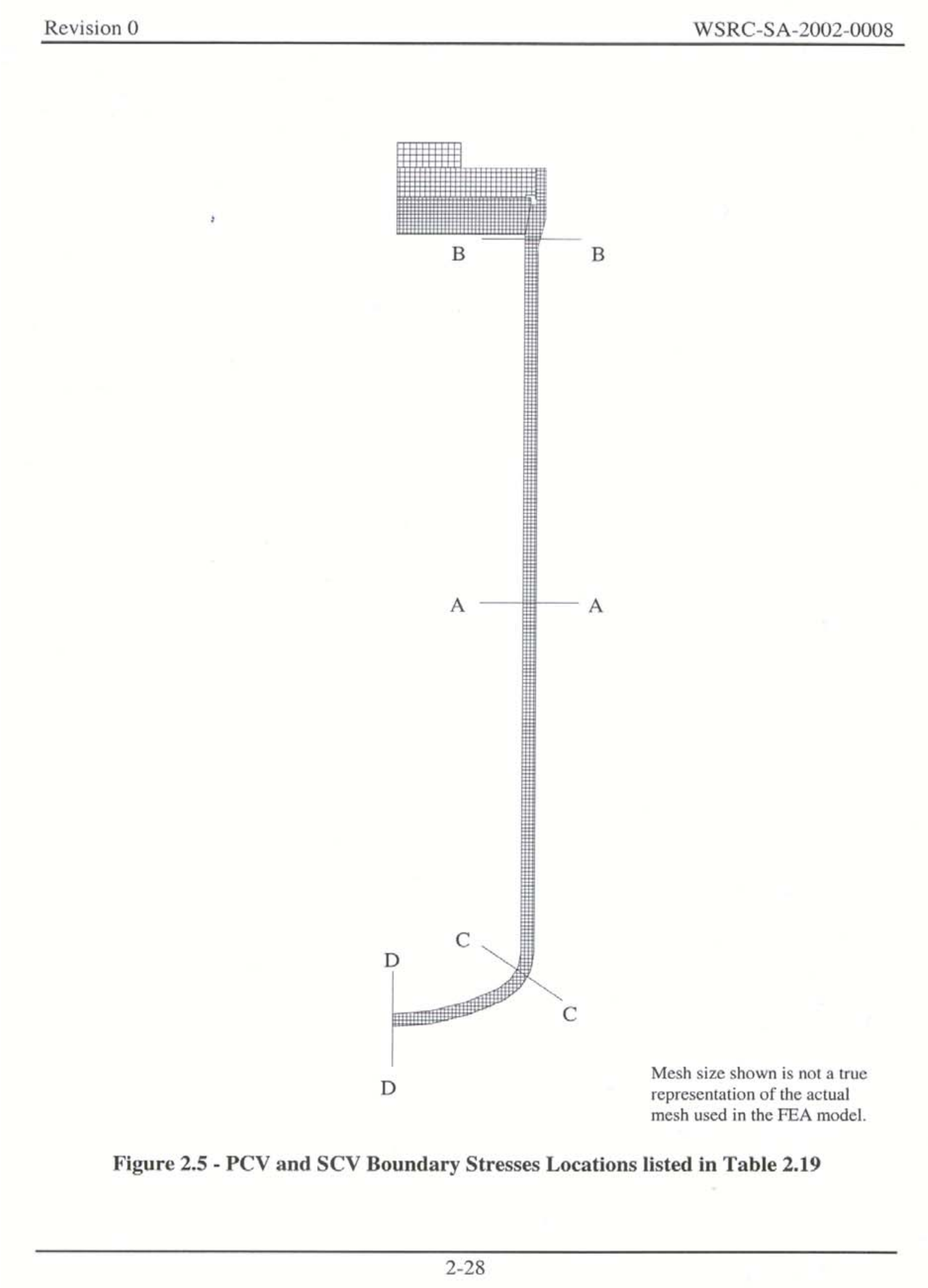
- Normally, the resulting dynamic FEA impact stress or force data are time-dependent and the time history plots show extreme high peaks at very high frequencies. As a result, it becomes difficult to estimate maximum principal stresses. Many of these high frequency peaks are high frequency acoustic noise. One suggested method for eliminating this high frequency noise is to filter the numerical simulation data at some cut-off frequency. This cut-off frequency is based on the suggested cut-off frequency for impact tests using acceleration sensors specified in paragraph 701.9 of the *IAEA Safety Standards Series* TS-G-1.1 (ST-2).[D-5] This paragraph states, "The cut-off frequency should be selected to suit the structure (shape and dimensions) of the package. Experience suggests that, for a package with a mass of 100 metric tonnes with impact limiters, the cut-off frequency should be 100 to 200 Hz and that for smaller packages with a mass of m metric tonne, this cut-off frequency should be multiplied by a factor $(100/m)^{1/3}$." Another suggested method is to manually determine the maximum principal stresses by ignoring the short period peaks and determining the maximum principal stress from the longest duration peaks.

- The other problem in applying dynamic FEA methods is that the stress data obtained from the numerical simulations are difficult to classify in accordance with ASME BPVC methods into primary membrane, primary bending, and

> secondary stress principal stresses, especially at joints and other discontinuities. As a result, specialized procedures must be used in classifying the principal stresses. These procedures basically linearize the stresses through a section to separate out the various stress components. Two such procedures are Kroenke's and Gordon's Procedures. Kroenke's procedure defines an equivalent linear stress distribution based on a reference or classification through the section. This procedure basically assumes a straight shell wall in the meridional direction. The Gordon procedure modifies the Kroenke's procedure for curved walls. However, it must be pointed out that both methods are for axisymmetrical loading conditions and must be adapted for three dimensional loading problems. Also, although these and other methods are under study by the ASME BPVC, none have yet been adopted. Recently, the ASME Pressure Vessel Research Council (PVRC) issued a report on stress categorization. The report is summarized in the 2000 issue of the *Journal of Pressure Vessel Technology* by Hollinger and Hechner titled *Three Dimensional Stress Criteria-Summary of the PVRC Project*.[D-6] This paper discusses several recommendations, but in summation, it is left to the ingenuity of the structural analyst to extract the principal stresses from any general finite element method. As a result, in many containment system FEA evaluations, the calculated stress intensities from the load combinations are conservatively assumed as primary membrane in the shell, and primary membrane plus bending at joints and discontinuities with only thermal stresses being considered as secondary throughout the member. Although this method is very conservative, in most cases, containment systems are of sufficient robustness that such conservatism will still show positive margins.

An example of the application of stress linearization procedures for classifying stresses from an FEA evaluation of internal pressure loading is shown in the example below. This method is used to demonstrate acceptable structural performance of the 9975 package under internal pressure and has been extracted from the Savannah River Site 9975 SARP, Appendix 2.2.[D-7] The example below is being provided only as an example of the stress linearization methods mentioned above. In this example, the impact stresses are calculated separately and the stress intensities are combined in another section. The example stress linearization method is for a section of the containment vessel near the top end closure (Section B-B as shown below).

Example of Stress Linearization Methods from the 9975 SARP



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Mesh size shown is not a true representation of the actual mesh used in the FEA model.

Figure 2.5 - PCV and SCV Boundary Stresses Locations listed in Table 2.19

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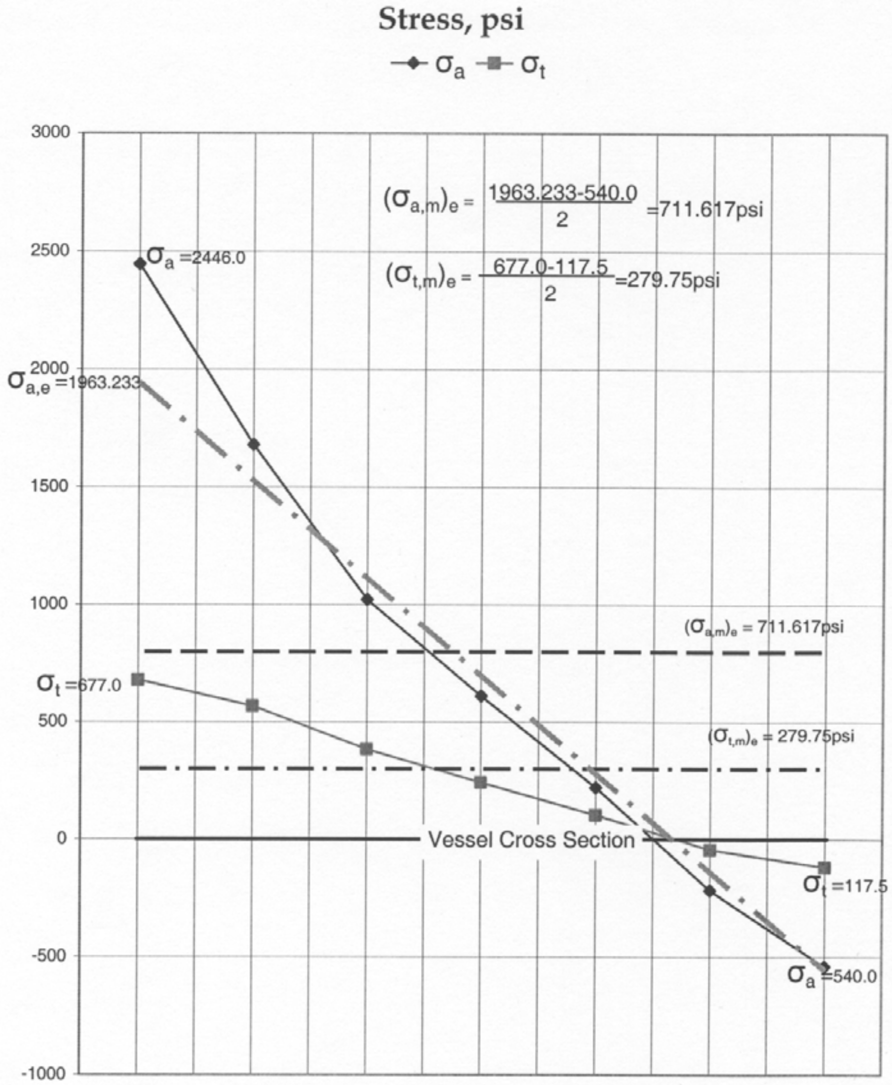

Figure 7. Equivalent Membrane and Bending Stresses on Section BB

The principal stresses in the planes perpendicular to the radial and axial directions are:

$$\sigma_1, \sigma_2 = \frac{\sigma_r + \sigma_a}{2} \pm \sqrt{\left(\frac{\sigma_r - \sigma_a}{2}\right)^2 + \tau_{ra}^2}$$

$$= \frac{24.32 + 711.617}{2} \pm \sqrt{\left(\frac{24.32 - 711.617}{2}\right)^2 + (-166.61)^2}$$

$$= 367.969 \pm 381.93$$

or,

$$\sigma_1 = 749.90\,\text{psi}$$

$$\sigma_2 = -13.96\ \text{psi}$$

The principal stresses in the three dimensional space then become:

$$\sigma_I = 763.86\ \text{psi}$$

$$\sigma_{II} = 279.75\ \text{psi}$$

$$\sigma_{III} = -13.96\ \text{psi}$$

Consequently, the primary membrane stress intensity is:

$$P_m = \sigma_I - \sigma_{III} = 763.86 + 13.96 = 777.82\ \text{psi}$$

(b) Primary Membrane Plus Primary Bending Plus Secondary Stress Intensity

The stress components are:

$$\sigma_r = -150\ \text{psi}$$

$$\sigma_a = \sigma_{a,e} = 1963\ \text{psi}$$

$$\sigma_t = 677\,\text{psi}$$

$$\tau_{ra} = 0$$

Then, the principal stresses are:

$$\sigma_1 = \sigma_a = 1963\,\text{psi}$$

$\sigma_2 = \sigma_t = 677\,\text{psi}$

$\sigma_3 = \sigma_r = -150\,\text{psi}$

Thus, the Primary Membrane Plus Primary Bending Plus Secondary Stress Intensity is:

$$P_m + P_b + Q = \sigma_1 - \sigma_3 = 1963 + 150 = 2113 \text{ psi}$$

(c) Primary Membrane Plus Primary Bending Plus Secondary Plus Peak Stress Intensity

The stress components are as follow:

$\sigma_r = -150.0 \text{ psi}$

$\sigma_a = 2446.0 \text{ psi}$

$\sigma_t = 677.0 \text{ psi}$

$\tau_{ra} = 0.0 \text{ psi}$

Then, the principal stresses are:

$\sigma_1 = \sigma_a = 2446.0 \text{ psi}$

$\sigma_2 = \sigma_t = 677.0 \text{ psi}$

$\sigma_3 = \sigma_r = -150.0\,\text{psi}$

Thus, the Primary Membrane Plus Primary Bending Plus Secondary Plus Peak Stress Intensity is:

$$P_m + P_b + Q + F = \sigma_1 - \sigma_3 = 2446.0 + 150.0 = 2596.0 \text{ psi}$$

4.2.2.3 Section C – C

The normal and shear stress components in the vessel axial and radial directions across Section C-C, Figure 6, obtained from the finite-element analysis are not the normal and shear stresses with respect to the Cross Section C-C. The normal and shear stresses on the surface of Section C-C can be calculated in terms of the finite-element results by using the following equations:

$$\sigma_n = \sigma_r \cos^2\alpha + \sigma_a \sin^2\alpha + 2\tau_{ra} \sin\alpha\cos\alpha$$

$$\tau_{nR} = \tau_{ar}(\cos^2\alpha - \sin^2\alpha) + (\sigma_a - \sigma_r)\sin\alpha\cos\alpha$$

References

D-1 NRC, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Regulatory Guide 7.6, Rev. 1, Washington, D.C., 1978.

D-2 ASME, *Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NB, New York, New York, 1977.

D-3 ASME, *Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NB, New York, New York, 2001.

D-4 ASME, *Boiler and Pressure Vessel Code*, Section III, Division 1, Appendices, New York, New York, 2001.

D-5 IAEA, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, Safety Guide*, Safety Standards Series No. TS-G-1.1 (ST-2), Vienna, Austria, 2002.

D-6 G. Hollinger and J. Hechner, *Three Dimensional Stress Criteria - Summary of the PVRC Project*, Journal of Pressure Vessel Technology, Vol. 122, American Society of Mechanical Engineers, New York, New York, 2000.

D-7 Savannah River Site, *Safety Analysis Report for Packaging Model 9975*, WSRC-SA-2002-00008, Rev. 0, Westinghouse Savannah River Company, Aiken, South Carolina, 2003