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REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 7.6

DESIGN CRITERIA FOR THE STRUCTURAL ANALYSIS OF SHIPPING CASK CONTAINMENT VESSELS

A. INTRODUCTION

Sections 71.35 and 71.36 of 10 CFR Part 71, "Packaging of Radioactive Material for Transport and Transportation of Radioactive Material Under Certain Conditions," require that packages used to transport radioactive materials meet the normal and hypothetical accident conditions of Appendices A and B, respectively, to Part 71. This guide describes design criteria acceptable to the NRC staff for use in the structural analysis of the containment vessels of Type B packages used to transport irradiated nuclear fuel. Alternative design criteria may be used if judged acceptable by the NRC staff in meeting the structural requirements of §§71.35 and 71.36 of 10 CFR Part 71.

B. DISCUSSION

At present, there are no design standards that can be directly used to evaluate the structural integrity of the containment vessels of shipping casks for irradiated fuels. This guide presents containment vessel design criteria that can be used in conjunction with an analysis which considers the containment vessel and other principal shells of the cask (e.g., outer shell, neutron shield jacket shell) to be linearly elastic. A basic assumption for the use of this guide is that the principle of superposition can be applied to determine the effect of combined loads on the containment vessel. However, use of this guide does not preclude appropriate nonlinear treatment of other cask components (e.g., impact limiters and lead shielding).

Design criteria for nonlinear structural analyses are not presented in this guide because of the present lack of data sufficient to formulate substantial nonlinear criteria. The NRC staff will review criteria other than those given in this guide on a case-by-case basis.

Section III of the ASME Boiler and Pressure Code[1] contains requirements for the design of nuclear power plant components. Portions of the Code that use a "design-by-analysis" approach for Class 1 components have been adapted in this guide to form acceptable design criteria for shipping cask containment vessels. The design criteria for normal transport conditions, as defined in 10 CFR Part 71, are similar to the criteria for Level A Service Limits (formerly called "normal conditions") of Section III, and the design criteria for accident conditions are similar to those for Level D Service Limits (formerly called "faulted conditions"). However, Section III was developed for reactor components, not fuel casks, and many of the Code's requirements may not be applicable to fuel cask design.

The criteria in this guide reflect the designs of recently licensed shipping casks. The containment vessels having these designs were made of austenitic stainless steel, which is ductile even at low temperatures. Thus, this guide does not consider brittle fracture. Likewise, creep is not discussed because the temperatures of containment vessels for irradiated fuel are characteristically below the creep range, even after the hypothetical thermal accident requirement of 10 CFR Part 71. The nature of the design cyclic thermal loads and pressure loads is such that thermal ratchetting is not considered a realistic failure mode for cylindrical containment vessels. Containment vessel designs that are significantly different from current designs (in shape, material, etc.) may necessitate the consideration of the above failure modes.

*Lines indicate substantive changes from previous issue.

[1] Copies may be obtained from the American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, N.Y. 10017.

Regulatory positions 2 and 6 ensure that failure due to gross unrestrained yielding across a solid section does not occur. Secondary stresses (i.e., stresses that are self-limiting) are not considered to cause gross unrestrained yielding but are considered in fatigue and shakedown analyses.

Regulatory position 3 ensures that fatigue failure does not occur, and regulatory position 4 ensures that the structure will shake down to elastic behavior after a few cycles. Both of these positions address only the stress range of normal operation. Recent studies[2] have shown that fatigue strength decreases beyond 10^6 cycles for certain materials. Regulatory position 3.b addresses the possibility of fatigue strength reduction beyond 10^6 cycles.

Regulatory position 5 states that buckling of the containment vessel should not occur. While it is recognized that local or gross buckling of the containment vessel could occur without failure (i.e., leakage), the stress and strain limits given in this guide are based on linear elastic analysis and are inappropriate for determining the integrity of a postbuckled vessel. If the analysis of a containment vessel indicates the likelihood of structural instability, the design criteria of this guide should not be used.

Regulatory position 7 places a limit on the extreme range of the total stresses due to the initial and fabrication states (see definition 9 below) and the normal operating and accident states of the containment vessel. The 10-cycle value of S_a (taken from the ASME design fatigue curves) is used. Because this value is in the extreme low-cycle range, this regulatory position is actually a limit on strain rather than stress.

Design criteria for bolted closures are not presented in this guide. Insufficient information exists, particularly for response to impact loading, to establish such criteria.

The following terms are presented with the definitions used in this guide:

1. *Stress intensity* means twice the maximum shear stress and is equal to the largest algebraic difference between any two of the three principal stresses.

2. *Primary stress* means a stress that is necessary to satisfy the laws of equilibrium of forces and moments due to applied loadings, pressure loadings, and body (inertial) loadings. Primary stresses are not self-limiting because local yielding and minor distortions do not reduce the average stress across a solid section.

3. *Secondary stress* means a stress that is self-limiting. Thermal stresses are considered to be secondary stresses since they are strain-controlled rather than load-controlled, and these stresses decrease as yielding occurs.

The bending stress at a gross structural discontinuity, such as where a cylindrical shell joins a flat head, is generally self-limiting and is considered to be a secondary stress. However, when the edge moment at the shell and head junction is needed to prevent excessive bending stresses in the head, the stress at the junction is considered a primary stress. The bending stress at a joint between the walls of a rectangular cross-section shell is considered a primary stress.

4. *Primary membrane stress* means the average normal primary stresses across the thickness of a solid section. *Primary bending stresses* are the components of the normal primary stresses that vary linearly across the thickness of a solid section.

5. *Alternating stress intensity,* S_{alt}, means one-half the maximum absolute value of S'_{12}, S'_{23}, S'_{31}, for all possible stress states i and j where σ_1, σ_2, and σ_3 are principal stresses and

$$S'_{12} = (\sigma_{1i} - \sigma_{1j}) - (\sigma_{2i} - \sigma_{2j})$$
$$S'_{23} = (\sigma_{2i} - \sigma_{2j}) - (\sigma_{3i} - \sigma_{3j})$$
$$S'_{31} = (\sigma_{3i} - \sigma_{3j}) - (\sigma_{1i} - \sigma_{1j})$$

σ_1, etc., follow the principal stresses as their directions rotate if the directions of the principal stresses at a point change during the cycle.

6. *Stresses caused by stress concentrations* means stress increases due to local geometric discontinuities (e.g., notches or local thermal "hot spots"). These stresses produce no noticeable distortions.

7. *Type B quantity* is defined in §71.4(q) of 10 CFR Part 71. *Normal conditions of transport* and *hypothetical accident conditions* are defined in Appendices A and B, respectively, to 10 CFR Part 71.

8. *Containment vessel* means the receptacle on which principal reliance is placed to retain the radioactive material during transport.

9. *Fabrication* means the assembly of the major components of the casks (i.e., the inner shell, shielding, outer shell, heads, etc.) but not the construction of the individual components. Thus, the phrase *fabrication stresses* includes the stresses caused by interference fits and the shrinkage of bonded lead shielding during solidification but does not include the residual stresses due to plate formation, welding, etc. The prefabrication state is designated as the *initial state* and is treated as having zero stress.

10. *Shakedown* means the absence of a continuing cycle of plastic deformation. A structure shakes down if, after a few cycles of load application, the deformation stabilizes and subsequent structural response is elastic.

[2] C. E. Jaske and W. J. O'Donnell, "Fatigue Design Criteria for Pressure Vessel Alloys," ASME Paper 77-PVP-12.

C. REGULATORY POSITION

The following design criteria are acceptable to the NRC staff for assessing the adequacy of designs for containment vessels of irradiated fuel shipping casks in meeting the structural requirements in §§71.35 and 71.36 of 10 CFR Part 71. References to the ASME Boiler and Pressure Vessel Code indicate the 1977 edition.

1. The values for material properties, design stress intensities (S_m), and design fatigue curves for Class 1 components given in Subsection NA of Section III of the ASME Boiler and Pressure Vessel Code should be used for the materials that meet the ASME specifications. For other materials, the method discussed in Article III–2000 of Subsection NA should be used to derive design stress intensity values. ASTM material properties should be used, if available, to derive design stress intensity values. The values of material properties that should be used in the structural analysis are those values that correspond to the appropriate temperatures at loading.

2. Under normal conditions, the value of the stress intensity resulting from the primary membrane stress should be less than the design stress intensity, S_m, and the stress intensity resulting from the sum of the primary membrane stresses and the primary bending stresses should be less than $1.5S_m$.

3. The fatigue analysis for stresses under normal conditions should be performed as follows:

a. S_{alt} is determined (as defined in the Discussion). The total stress state at each point in the normal operating cycle should be considered so that a maximum range may be determined.

b. The design fatigue curves in Appendix I of Section III of the ASME Boiler and Pressure Vessel Code should be used for cyclic loading less than or equal to 10^6 cycles. Consideration should be given to further reduction in fatigue strength when loading exceeds 10^6 cycles.

c. S_{alt} should be multiplied by the ratio of the modulus of elasticity given on the design fatigue curve to the modulus of elasticity used in the analysis to obtain a value of stress to be used with the design fatigue curves. The corresponding number of cycles taken from the appropriate design fatigue curve is the allowable life if only one type of operational cycle is considered. If two or more types of stress cycles are considered to produce significant stresses, the rules for cumulative damage given in Article NB–3222.4 of Section III of the ASME Boiler and Pressure Vessel Code should be applied.

d. Appropriate stress concentration factors for structural discontinuities should be used. A value of 4 should be used in regions where this factor is unknown.

4. The stress intensity, S_n, associated with the range of primary plus secondary stresses under normal conditions should be less than $3S_m$. The calculation of this stress intensity is similar to the calculation of $2S_{alt}$; however, the effects of local stress concentrations that are considered in the fatigue calculations are not included in this stress range.

The $3S_m$ limit given above may be exceeded if the following conditions are met (these conditions can generally be met only in cases where the thermal bending stresses are a substantial portion of the total stress):

a. The range of stresses under normal conditions, excluding stresses due to stress concentrations and thermal bending stresses, yields a stress intensity, S_n, that is less than $3S_m$.

b. The value S_a used for entering the design fatigue curve is multiplied by the factor K_e, where:

$$K_e = 1.0, \text{ for } S_n \leq 3S_m$$
$$= 1.0 + \frac{(1-n)}{n(m-1)}\left(\frac{S_n}{3S_m} - 1\right), \text{ for } 3S_m < S_n < 3mS_m$$
$$= \frac{1}{n}, \text{ for } S_n \geq 3mS_m$$

S_n is as described in regulatory position 4.a.

The values of the material parameters m and n are given for the various classes of materials in the following table:

			Tmax	
	m	n	°F	°C
Low-Alloy Steel	2.0	0.2	700	371
Martensitic Stainless Steel	2.0	0.2	700	371
Carbon Steel	3.0	0.2	700	371
Austenitic Stainless Steel	1.7	0.3	800	427
Nickel-Chromium-Iron	1.7	0.3	800	427

c. The temperatures do not exceed those listed in the above table for the various classes of materials.

d. The ratio of the minimum specified yield strength of the material to the minimum specified ultimate strength is less than 0.8.

5. Buckling of the containment vessel should not occur under normal or accident conditions. Suitable factors should be used to account for eccentricities in the design geometry and loading. An elastic-plastic buckling analysis may be used to show that structural instability will not occur; however, the vessel should also meet the specifications for linear elastic analysis given in this guide.

6. Under accident conditions, the value of the stress intensity resulting from the primary membrane stresses should be less than the lesser value of $2.4S_m$ and $0.7S_u$ (ultimate strength); and the stress intensity resulting from the sum of the primary membrane stresses and the primary bending stresses should be less than the lesser value of $3.6S_m$ and S_u.

7. The extreme total stress intensity range between the initial state, the fabrication state (see definition 9 in the Discussion), the normal operating conditions, and the accident conditions should be less than twice the adjusted value (adjusted to account for modulus of elasticity at the highest temperature) of S_a at 10 cycles given by the appropriate design fatigue curves.

Appropriate stress concentration factors for structural discontinuities should be used. A value of 4 should be used in regions where this factor is unknown.