U.S. NUCLEAR REGULATORY COMMISSION February 1977

REGULATORY GUIDE

OFFICE OF STANDARDS DEVELOPMENT

REGULATORY GUIDE 7.6

STRESS ALLOWABLES FOR THE DESIGN 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," establish requirements that packages used to transport radioactive materials must meet under normal and hypothetical accident conditions. 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. However, Section III of the ASME Boiler and Pressure Vessel Code* contains requirements for the design of nuclear power plant components. The staff has adapted portions of Section III of the ASME Code to form acceptable design criteria for shipping cask containment vessels. In this guide, the design criteria for shipping cask containment vessels for normal conditions (as defined in 10 CFR Part 71) are similar to the design criteria in Section III of the ASME Code for Class 1 components under normal conditions and the design criteria for accident conditions are similar to those for faulted conditions in the ASME Code.

The design criteria presented here are based primarily on linear elastic analyses. Linear elastic analyses are simpler than true elastic-plastic analyses, and they allow the use of superposition in summing loading effects. Design stress intensities are used because established material values for this use exist in the ASME Code and because this approach is based on the maximum shear stress theory, which has been shown to be a conservative estimate of the stress combinations that cause plastic deformation relative to experimental data.

In current designs for the containment vessels of fuel casks, the nature of the temperature and pressure loads and the containment vessel material (stainless steel) are such that creep and brittle fracture are not considered to present problems. Thermal ratchetting is not considered to cause difficulties in cylindrical containment vessels.

Regulatory Positions 3 and 7 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 analysis.

Regulatory Position 4 ensures that fatigue failure does not occur, and Regulatory Position 5 ensures that the structure will shake down to elastic behavior after a few cycles. Both of these positions deal only with the stress range of normal operation. A reduction in the allowable stress for life exceeding 10^6 cycles is specified in Regulatory Position 4 since use of the 10^6 cycle value for greater lives may not preserve an adequate design margin for all cases.

Regulatory Position 8 places a limit on the extreme range of the total stresses due to initial fabrication and the normal operating and accident states of the containment vessel.

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

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

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

2. A *primary stress* is 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. A *secondary stress* is 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 to be a primary stress. The bending stress at a joint between a rectangular shell and a flat head is unrestrained by hoop effects and will be considered to be a primary stress.

4. *Primary membrane stresses* are 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. The *alternating stress intensity*, S_{alt}, is defined as 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

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

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. The phrase *stresses caused by stress concentrations* refers to increases in stresses 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* is defined as the receptacle on which principal reliance is placed to retain the radioactive material during transport.

C. REGULATORY POSITION

The following design criteria are acceptable to the NRC staff for assessing the adequacy of designs for shipping cask containment vessels in meeting the structural requirements in §§71.35 and 71.36 of 10 CFR Part 71.

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 listed in that subsection. For materials not listed there, 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 that correspond to the appropriate temperatures at loading.

2. Strain-rate-sensitive material properties may be used in the evaluation of impact loading if the values used are appropriately considered in a dynamic time-dependent analysis and can be suitably justified in the license application.

When strain rate sensitivity is considered in the structural response to a combination of static and dynamic loads, the static portion of the stresses and strains should be analyzed separately using static material properties and should meet the static design criteria. The total stress and strain state resulting from both static and dynamic loads should meet the design criteria for which strain-rate-sensitive material properties (e.g., yield strength) are substituted for static values.

3. Under normal conditions the value of the stress intensity resulting from the primary membrane stresses 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 $1.5S_m$.

4. 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 (Figures I-9.0) of Section III of the ASME Boiler and Pressure Vessel Code should be used. These curves include the maximum mean stress effect.

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. In the analysis of high cycle fatigue where the number of cycles exceeds 10^6 cycles, the ASME design fatigue curves should be extended using a 4% decrease in the allowable stress per decade, starting from the 10^6 cycle value. High cycle fatigue could be a potential problem due to vibration during transportation.

e. A value of 4 should be used as the maximum stress concentration factor in regions where this factor is unknown.

5. 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 secondary 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 secondary 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:

$$
\begin{aligned}
K_e &= 1.0\,(S_n \leq 3S_m) \\
&= 1.0 + \frac{(1 - n)}{n(m - 1)}\left(\frac{S_n}{3S_m} - 1\right)(3S_m < S_n < 3mS_m) \\
&= \frac{1}{n}\quad (S_n \geq 3mS_m)
\end{aligned}
$$

S_n is as described in a.

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

	m	n	T_{max}, °F
Low Alloy Steel	2.0	0.2	700
Martensitic Stainless Steel	2.0	0.2	700
Carbon Steel	3.0	0.2	700
Austenitic Stainless Steel	1.7	0.3	800
Nickel-Chromium-Iron	1.7	0.3	800

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 0.80.

6. Buckling of the containment vessel should not occur under normal and accident conditions.

7. 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.

8. The extreme total stress intensity range between the initial zero stress state, fabrication, normal operation, and 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.

A value of 4 should be used as the maximum stress concentration factor in regions where this factor is unknown.

9. In some cask designs, shielding materials apply loads through differential thermal expansion or supply additional strength to the containment vessel. In such cases, shielding materials that have low yield strengths (e.g., lead) may be structurally analyzed using an elastic-plastic technique while the inner shell is analyzed by a linear elastic analysis. When uranium is used for shielding and is needed to add strength to the containment vessel, the fracture behavior of the uranium shielding should be considered.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which the applicant or licensee proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the design criteria described herein will be used by the staff after October 1, 1977, in assessing the adequacy of designs for containment vessels of packages for shipping irradiated fuel with respect to the structural requirements in §§71.35 and 71.36 of 10 CFR Part 71. When alternative criteria are proposed, the applicant or licensee should demonstrate that their use satisfies the requirements of §§71.35 and 71.36 of 10 CFR Part 71.