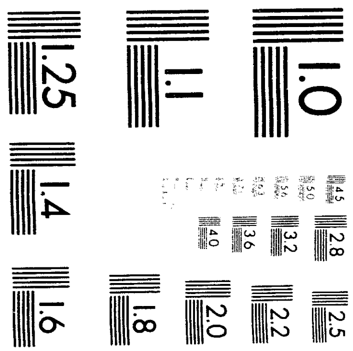


Conf-930702--52

UCRL-JC-113476
NRC FIN No. A0291
PREPRINT

Structural Analysis of Closure Bolts For Shipping Casks

Gerald C. Mok
Larry E. Fischer

This paper was prepared for submittal to the
1993 ASME Pressure Vessels & Piping Conference
Denver, CO
July 25-29-1993

April 1993

Lawrence Livermore National Laboratory

STRUCTURAL ANALYSIS OF CLOSURE BOLTS FOR SHIPPING CASKS*

Gerald C. Mok and Larry E. Fischer
Fission Energy and Systems Safety Program
Lawrence Livermore National Laboratory
Livermore, California

ABSTRACT

This paper identifies the active forces and moments in a closure bolt of a shipping cask. It examines the interactions of these forces/moments and suggests simplified methods for their analysis. The paper also evaluates the role that the forces and moments play in the structural integrity of the closure bolt and recommends stress limits and desirable practices to ensure its integrity.

INTRODUCTION

Bolts are widely used for joints and closures. A voluminous literature exists concerning the behavior and design of bolts and bolted joints. The original report of this work (Mok, Fischer, and Hsu, 1993) contains a list of existing publications on the subject. No publications, however, have specifically addressed the design needs of closure bolts for shipping casks. For example, Appendix XII (Design Considerations for Bolted Flange Connections) of the ASME Boiler and Pressure Vessel Code, Section III (ASME, 1989) has pointed out that the established ASME stress analysis procedure in Appendix XII for bolted flanges may not be applicable to situations with high temperatures and large (flange) diameters, which are two conditions that may be present in bolted closure joints of shipping casks. In addition to high temperatures and large closure, closure bolts in shipping casks may experience severe axial and transverse impact loads. In view of the need for a specific stress analysis method for the closure bolts of shipping casks, this work was undertaken. The approach taken was to apply existing knowledge and understanding of the behavior of bolted joints to the special design conditions and requirements of closure bolts for shipping casks.

The Federal regulation for the packaging and transportation of radioactive material (OFR, 1992) imposes strict limits on the permissible leakage of radioactive material through the containment system of shipping casks. The limits are to be maintained under a specified set of normal conditions of transport as well as under a set of hypothetical accident conditions. To meet the leakage limits, all components of the bolted joint, which consist of the cask wall, the closure lid, the closure bolts, and the gasket of the containment system, must first be structurally sound under the normal and the hypothetical conditions of transport. The present paper, however, deals only with the structural integrity of the closure bolts and not the other components. An adequate design of the bolted closure will need similar attention to the structural integrity of the other components. Moreover, the leaktight quality of the joint would depend on the selection of bolt preload and gaskets or seals.

To establish the necessary stress analysis method and criteria for the closure bolts, this paper identifies first the major forces and moments in a closure bolt and their possible causes. The paper then discusses the interactions and the significance of these forces and moments in the structural integrity of the closure bolts. The discussion continues into the specification of analysis methods, stress limits,

*This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

and desirable practices in the design and use of closure bolts. Stress limits are defined for both the normal and the hypothetical conditions of transport. Details of the development and basis of the presented information are not included but can be found in the original report (Mok, Fischer, and Hsu, 1993).

BOLT FORCES AND MOMENTS

Figure 1 depicts a typical shipping cask with a bolted closure. Figure 2 illustrates all major forces and moments that a bolt in the closure joint may experience at various times in its life. The forces and moments can include an axial (tensile) force, a transverse (shear) force, a bending moment, and a torsional moment.

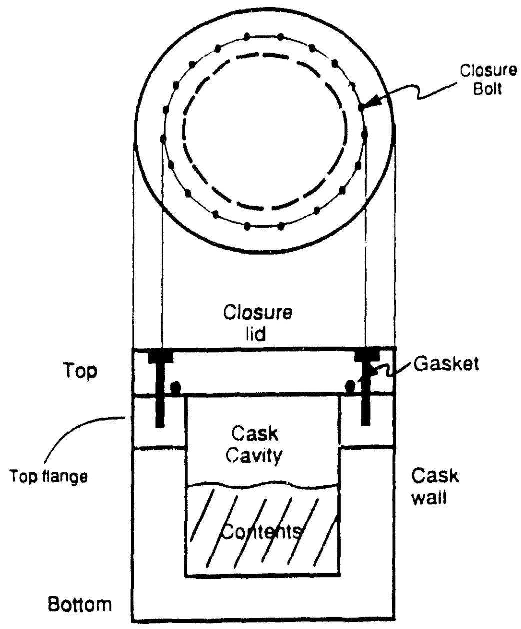


FIGURE 1. SHIPPING CASK SHOWING CLOSURE BOLT POSITIONS

An applied load on the closure or closure joint can cause all the forces and moments in the closure bolt except the torsional moment, which is generated only when the bolt is preloaded by using a torque wrench. The preloading of a closure bolt is done to generate in the bolt an initial axial tensile force, which is known to provide many benefits to the bolt and bolted joint, for example, maintaining leak-tight quality, reducing fatigue damage, preventing vibration loosening, increasing resistance to transverse load of the bolted joint.

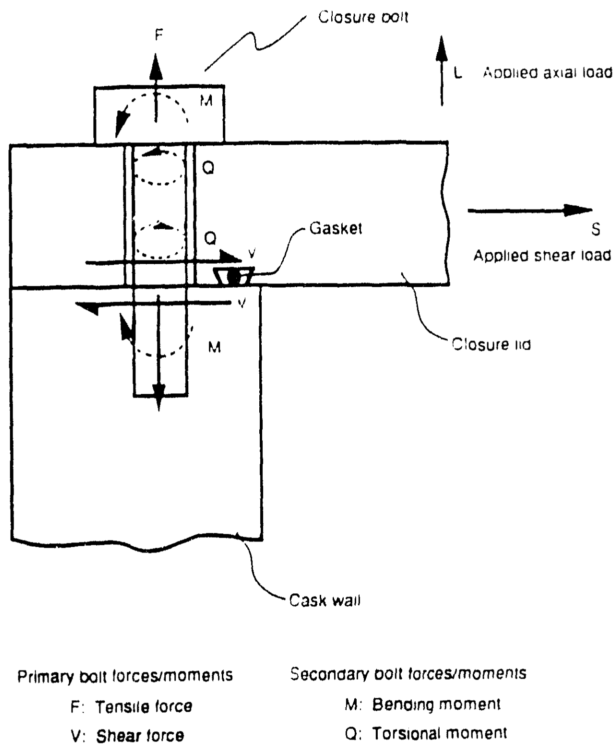


FIGURE 2. COMPONENTS OF A SHIPPING-CASK BOLTED CLOSURE AND FORCES WHICH MAY EXIST IN A CLOSURE BOLT

In preloading with a torque wrench, the bolt is stretched indirectly. The torque is applied first to overcome the friction between the bolt and the joint, and then to rotate the bolt about its own axis. The rotation effects an advancement of the bolt into its counterpart and causes a compression in the bolted joint and a tension (preload) in the bolt. The preload achieved is determined by the applied torque and the friction between the bolt and the joint. An approximate empirical relation is used to relate the applied torque to the achieved preload. Because of uncertainties in the friction, the preloading by a torque wrench is an imprecise operation. Experience has shown that using a given torque the resulting preload can have a scatter as large as ±30% of its average magnitude (Bickford, 1990). This large uncertainty in the preload should be properly considered in the selection of preload and stress limits for closure bolts. (More precise methods of preloading are available but less convenient to use than the torque wrench.)

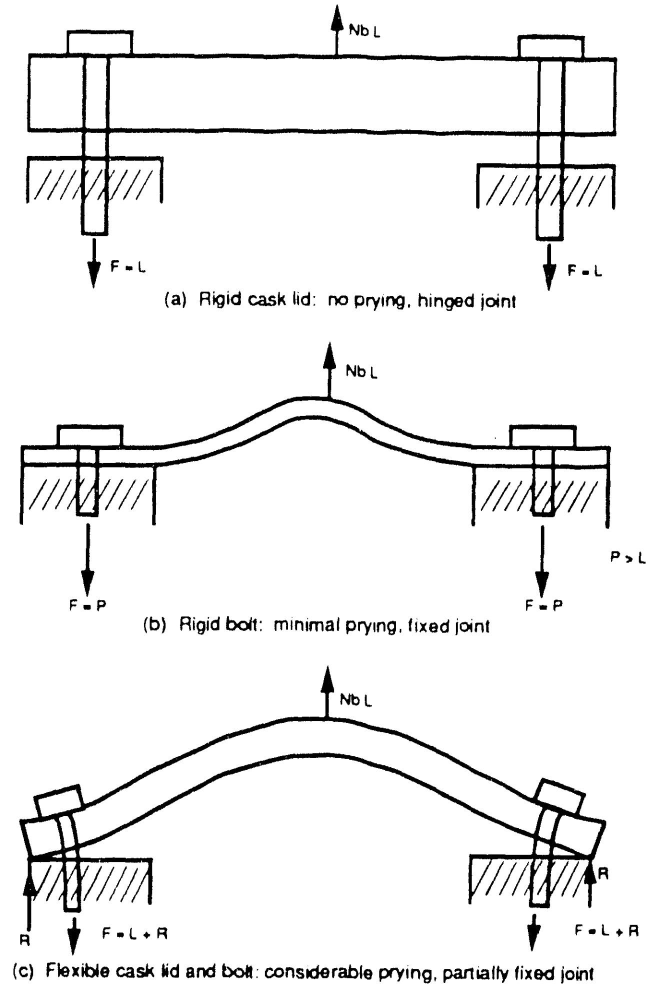
By design, a bolt acts like a one-dimensional structural member. It is most capable of resisting deformation in its axial direction, and most loads applied to the bolted joint would induce an axial force in the bolt. Therefore, the axial force is the primary force causing possible structural failure of the closure bolt.

A tensile axial bolt force can be generated directly or indirectly by applied loads. The bolt force generated directly is the force required to maintain equilibrium with the applied load. The force generated indirectly is due to the deformation of the components of the bolted joint. Figure 3 demonstrates the cause for such a force (the prying bolt force). In Figure 3, the bolt forces generated directly and indirectly are labeled as L and R, respectively. The force L required to maintain equilibrium with the applied load has the same magnitude as the applied load. The magnitude of the force R depends on the deformations of the the closure lid, the cask wall, and the bolt, as demonstrated in Figure 3 for different deformations of the closure lid.

The prying force, R, can be significant in casks of large diameter. The original report of this work (Mok, Fischer and Hsu, 1993) has derived and verified a set of approximate formulas for the evaluation of the prying force generated by a circular flat closure lid. Using the formulas, the report has also demonstrated the following: (1) A closure lid having adequate thickness to support the applied load without permanent deformation may not have sufficiently stiffness to avoid the generation of a significant prying bolt force; (2) A preload tends to enhance rather than reduce the prying action, and the maximum prying force occurs when the applied load nearly equals the preload; and (3) A closure lid of one uniform thickness produces a greater prying action than a lid of two thicknesses.

The transverse shear bolt force is responsible for resisting the sliding of the closure lid along the top of the cask wall. Closure bolts are relatively ineffective in resisting sliding, and the sliding motion can be detrimental to the gasket or seal of the joint. Therefore, a "tongue-and-groove" closure lid is preferred to support the closure lid in the transverse direction. In this case, the shear bolt force tends to be insignificant in magnitude and can be ignored in the stress analysis of the closure bolt. On the other hand, if the closure bolt is the only component resisting the transverse motion, then the shear bolt force should be conservatively evaluated by ignoring the joint friction.

The bending moment in the closure bolt has the nature of a secondary load (or stress) as defined in Subsection NB of The ASME B&PV Code (ASME, 1989). A secondary load is caused mainly by constraint, and its magnitude is controlled primarily by the deformation rather than by the applied load. This is the case with the bending moment in the closure bolt. The yielding of the bolt or the joint material would immediately limit the magnitude of the bending moment. Moreover, the original report of this work (Mok, Fischer and Hsu, 1993) has shown that for shipping casks



(a) Rigid cask lid: no prying, hinged joint

(b) Rigid bolt: minimal prying, fixed joint

(c) Flexible cask lid and bolt: considerable prying, partially fixed joint

FIGURE 3. THE DEPENDENCE OF PRYING AND JOINT BEHAVIOR ON THE RELATIVE FLEXIBILITY OF BOLTED JOINT COMPONENTS

with a circular closure lid, the prying action of a deformed closure lid would cause a greater percentage increase in the axial force than in the bending moment of the bolt. Therefore, the bending moment poses not only a limited but also an insignificant threat to the structural integrity of closure bolts for shipping casks. For this reason, the stress acceptance criteria suggested later in this paper for the hypothetical accident conditions do not consider the bending moment.

INTERACTION OF BOLT FORCES/ MOMENTS

A bolted closure joint is a highly redundant (or constrained) structure. Therefore, the bolt forces and moments can be interrelated and depend on the preload, the applied load, and the deformation of the bolted closure joint. The preceding section has already identified the relationships between the bolt preload and the applied torque, between the shear bolt force and the joint friction, and between the bolt prying force/bending moment and the deformation of the closure lid. A valid stress analysis of the closure bolt should properly include all significant interactions of the bolt forces and moments.

Among all bolt forces and moments, the axial bolt force involves most interactions. Figure 4 demonstrates the interaction of the axial bolt forces from the various causes, namely, the preload (P), the applied load (L), and the prying action (R). The figure illustrates the following:

- For practical purposes, the bolt force can be considered equal to the preload before the applied load exceeds the preload. After the applied load exceeds the preload the bolt load is equal to the applied load.
- The bolt force due to prying snould be added to the bolt force due to the preload or to the applied load.

To preserve the relationship among the various bolt forces/moments, the following stress analysis procedure is suggested for the axial bolt force:

(1) Calculate the bolt preload from the preload torque; then add the axial bolt force due to the temperature difference between the bolt and the cask lid to obtain the resultant preload (P).

(2) Calculate the axial bolt forces due to all simultaneous applied loads to obtain the applied load (L).

(3) Use the larger of the resultant preload (P) and the applied load (L) as the resultant (non-prying) bolt load.

(4) Use the resultant (non-prying) bolt force and the closure lid and bolt deformations generated by the applied load (L) to calculate the prying bolt force (R).

(5) Add the prying bolt force to the resultant (non-prying) bolt force (L or P) to obtain the total bolt force.

(6) Compare the total bolt force to the allowable.

The shear bolt force and bending moment can be simply and conservatively obtained from the applied load by ignoring their interactions with other bolt forces and moments.

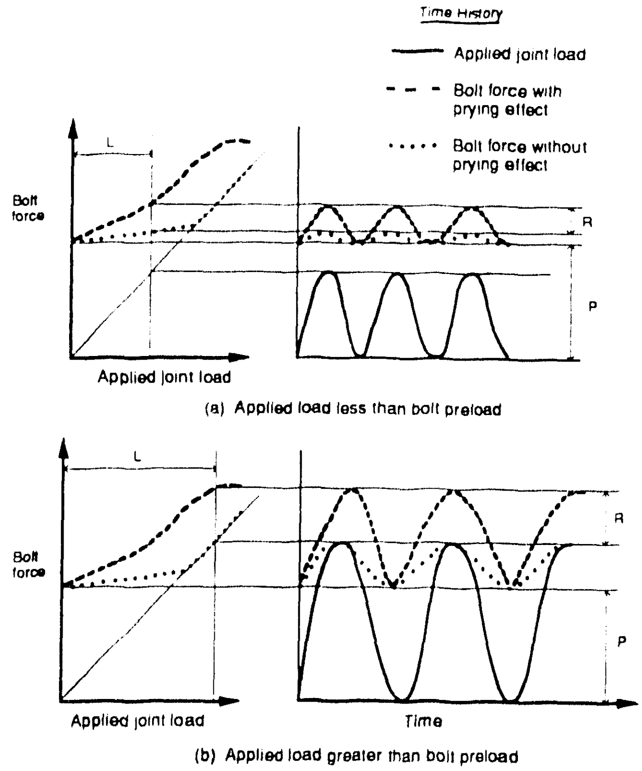


FIGURE 4. TENSILE BOLT FORCES GENERATED BY A FLUCTUATING APPLIED TENSILE LOAD

The original report (Mok, Fischer, and Hsu, 1993) contains detailed procedures for the evaluation of all bolt forces and moments.

STRESS LIMITS

The stress criteria recommended here and in the original report (Mok, Fischer, and Hsu, 1993) basically follow the principle set forth in the the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB for the design of Class 1 (the most safety-related) nuclear power plant components (ASME, 1989). Tables 1 through 3 summarize the recommendations.

High-strength bolt materials have limited ductility. It is essential to follow the ASME Code requirements for impact testing of bolts (Table 4). Appendix G of the ASME Code (ASME, 1989) states that the test requirement is sufficient to prevent the fracture of bolts under normal operation conditions of a nuclear power plant.

TABLE 1. STRESS ANALYSIS OF CLOSURE BOLTS—NORMAL CONDITIONS, PART I, MAXIMUM STRESS ANALYSIS

Load Cases To Be Considered	Limits on Bolt Stresses Obtained Using Elastic Analysis
Gasket-seating load or the maximum applied preload Load combinations of all normal condition loads plus the minimum gasket load: Operating preload Minimum gasket load Pressure load Temperature load Impact load Vibration load	Sy: Minimum yield stress or strength of the bolt material Sm: Basic allowable stress limit for the bolt material, equal to 2/3 of Sy at the room temperature or 2/3 of Sy at the operating temperature, whichever is less. **All of the following limits must be met:** Tension Average stress < Sm (Allowable stress) Shear Average stress < 0.6 Sm (Allowable stress) Tension plus shear Stress ratio = computed average stress/allowable average stress Rt: Stress ratio for average tensile stress Rs: Stress ratio for average shear stress $Rt^2 + Rs^2 < 1$ Tension plus shear plus bending plus residual torsion For bolts having minimum tensile strength (Su) less than 100 ksi Maximum stress intensity < 1.5 Sm For bolts having minimum tensile strength (Su) greater than 100 ksi Maximum stress intensity < 1.35 Sm
Notes: The effect of prying, bending and residual torsional shear should be included. None of the normal loads are expected to govern the bolt design. The maximum applied preload is usually the worst load. See Subsection 6.5 for additional information.	Notes: See Subsection 6.3 for the basis of the stress limits. In the absence of bending and residual torsion, the tensile and shear stresses are governed by the limits on the average stresses. The limit for the combined stress condition is less restrictive, unless all stresses are present.

TABLE 2. STRESS ANALYSIS OF CLOSURE BOLTS—NORMAL CONDITIONS, PART II, FATIGUE STRESS ANALYSIS

Load Histories To Be Considered	Acceptance Criteria
Repeated applied preload Load combinations of all normal condition loads plus the minimum gasket load: Operation preload Minimum gasket load Pressure load Temperature load Impact load Vibration load	**Maximum cumulative usage factor (U) due to alternating stress intensity < 1.0** For bolts having minimum yield strength less than 100 ksi Use ASME Code, Section III, Appendix I, fatigue curves I-9.0 with elastic-modulus adjustment Use fatigue strength reduction factor not less than 4.0, unless it can be shown otherwise For bolts with minimum yield strength greater than 100 ksi Use ASME Code, Section III, Appendix I, fatigue curves I-9.4 with elastic-modulus adjustment Use fatigue strength reduction factor not less than 4 Thread shall be Vee-type having minimum root radius no less than 0.003 in. Fillet radius at the end of the shank shall be such that the ratio of fillet radius to shank diameter is not less than 0.060 in.
Notes: The effect of prying, bending and residual torsional shear should be included. The repeated preload is usually the worst load, and it should be used to determine the allowable life of the closure bolt. The vibration load is not expected to be significant unless a resonance condition exists or excessive bending and prying action are present. Modify the design to eliminate these conditions. See Subsection 6.5 for additional information.	Notes: The specified fatigue curves are given in ASME BPV Code, Section III, Appendix I (Ref. 3).

TABLE 3. STRESS ANALYSIS OF CLOSURE BOLTS—ACCIDENT CONDITIONS, MAXIMUM STRESS ANALYSIS

Loads To Be Considered	Limits on Bolt Stresses Obtained Using Elastic Analysis
All accident condition loads: Impact Puncture Fire (temperature and pressure) Submersion (pressure)	Sy: Minimum yield stress or strength of the bolt material Su: Minimum ultimate stress or strength of the bolt material
	All of the following limits must be met: Tension Average stress < The smaller of 0.7 Su or Sy at temperature (Allowable stress) Shear Average stress < The smaller of 0.42 Su or 0.6 Sy at temperature (Allowable stress) Tension plus shear Stress ratio = computed average stress/allowable average stress Rt: Stress ratio for average tensile stress Rs: Stress ratio for average shear stress $Rt^2 + Rs^2 \leq 1$
Notes: The effect of the operating preload, bending and prying should be included. The impact load and the combined preload and fire load are expected to govern the bolt design. See Subsection 6.5 for additional information.	Notes: See Subsection 6.3 for the basis of the stress limits. The limit for the combined stress condition is less restrictive, unless all stresses are present.

RECOMMENDED PRACTICES

The present study has identified the following desirable practices in the design and use of bolted closure for shipping casks:

- Use protected closure lids and bolts to avoid the shear load generated by a direct impact on the closure system.
- Use one or more of the following methods to minimize bolt prying and bending, which can cause excessive bolt stress and fatigue:
  - Use a thick or stiffened closure lid.
  - Avoid using a lid of single uniform thickness.
  - Minimize the diameter of the closure lid or bolt circle.
  - Locate applied loads close to the cask wall or bolts.
  - Protect the closure lid from large applied loads.
  - Isolate the bolted joint from rotation transmitted from the closure lid and the cask wall.
  - Use sufficient preload to minimize leakage and fatigue, but avoid setting the preload value near the magnitude of the dominant applied load.
- Use anti-vibration-loosening devices or other methods to maintain a steady preload.
- Use gaskets (or seals) whose ability to maintain sealing does not vary significantly with the force and preload of the closure bolts.
- Minimize conditions like the misalignment of components or large bolt hole clearances that can lead to significant bolt bending.
- Use bolts, gaskets, lubricants, and bolt tightening procedures that minimize friction and resulting preload variations.
- Maintain an adequate quality assurance program to preclude the use of counterfeit, bogus, defective, and damaged bolts.
  - Conduct destructive and non-destructive acceptance tests of the bolts prior to the first use and independently of the supplier.
  - Visually inspect each bolt and its counterpart for unacceptable damage prior to each shipment.

TABLE 4. ASME SECTION III REQUIREMENTS FOR BOLTING MATERIAL OF CLASS 1 COMPONENTS

<table>
<tr><th>Requirement Category</th><th>Requirements</th><th>Code Section for Details</th></tr>
<tr><td>General</td><td>Bolt & stud material: Meet specification no. listed in Appendix I, Table I-1.3

Nut material: Meet specification no. listed in Appendix I, Table I-1.3 or SA-194

Washer material: Made of wrought material</td><td>NB2128</td></tr>
<tr><td>Fracture toughness</td><td>All bolting material including bolt, stud, and nut:

Bolt, stud, and nut of nominal size > 1.0 in. shall be impact tested using the Charpy V-notch (Cv) method.

Specimens from the bolting material shall be oriented in the axial direction and the notch normal to the surface.

Three specimens shall be tested at the lower of the preload temperature or the lowest service temperature.

All three specimens shall meet the following Cv requirement:
<table>
<tr><th>Nominal diameter</th><th>Lateral expansion, mils</th><th>Absorbed energy, ft-lb</th></tr>
<tr><td>1 in. or less</td><td>No test required</td><td>No test required</td></tr>
<tr><td>Over 1 in. to 4 in., incl.</td><td>25</td><td>No requirement</td></tr>
<tr><td>Over 4 in.</td><td>25</td><td>45</td></tr>
</table>
One test shall be made for each lot of material.</td><td>NB2311(a)
NB2322.2 (a)
NB2333
NB2345</td></tr>
<tr><td>Examination</td><td>
<table>
<tr><th>Nominal size</th><th>Required examinations</th></tr>
<tr><td>1 in. or less</td><td>Visual in accordance with NB2582</td></tr>
<tr><td>Over 1 in. to 2 in., incl.</td><td>Visual plus the magnetic particle or the liquid penetrant</td></tr>
<tr><td>Over 2 in. to 4 in., incl.</td><td>Visual plus the magnetic particle or the liquid penetrant, plus the ultrasonic as required by NB2585</td></tr>
<tr><td>Over 4 in.</td><td>Visual plus the magnetic particle or the liquid penetrant, plus the ultrasonic as required by NB2586</td></tr>
</table>
</td><td>NB2580</td></tr>
</table>

GERALD MOK

CONCLUSION

The present study has shown that the structural behavior of a bolted closure of shipping cask depends on many factors. Among the factors are the applied load, the preload, and the deformations of the bolt and the closure lid. To aid the design and evaluation of the closure bolt, this paper discussed the significance, the possible causes, and the interactions of bolt forces and moments. This paper has also outlined a set of procedures and acceptance criteria for the stress analysis of the closure bolts. Some desirable practices in the design and use of the closure bolt have also been identified.

ACKNOWLEDGMENT

The authors wish to thank Dr. Henry Lee of the U.S. Nuclear Regulatory Commission for his technical guidance of the original work.

REFERENCES

American Society of Mechanical Engineers (ASME), 1989, *Boiler and Pressure Vessel Code, Section III (Rules for Construction of Nuclear Power Plant Components)*, New York.

Bickford, J.H., 1990, *An Introduction to the Design and Behavior of Bolted Joints*, Second Edition, Marcel Dekker, Inc., New York.

Mok, G.C., Fischer, L.E., and Hsu, S.T., 1993, "Stress Analysis of Closure Bolts for Shipping Casks," U.S. Nuclear Regulatory Commission report NUREG/CR-6007.

Office of the Federal Register (OFR), National Archives and Records Administration, "Packaging and Transportation of Radioactive Materials," *Title 10, Code of Federal Regulations, Part 71*, Washington, DC.

DATE
FILMED
1 / 3 / 94
END