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AN APPROACH FOR THE DESIGN OF CLOSURE BOLTS OF SPENT FUEL ELEMENTS TRANSPORTATION PACKAGES

Miguel Mattar Neto[1], Carlos A. J. Miranda[2], Gerson Fainer[3]

[1,2,3] Nuclear and Energy Research Institute, IPEN-CNEN/SP
Av. Lineu Prestes, 2242 (São Paulo, SP, Brazil)
[1]mmattar@ipen.br, [2]cmiranda@ipen.br, [3]gfainer@ipen.br

ABSTRACT

The spent fuel elements transportation packages must be designed for severe conditions including significant fire and impact loads corresponding to hypothetical accident conditions. In general, these packages have large flat lids connected to cylindrical bodies by closure bolts that can be the weak link in the containment system. The bolted closure design depends on the geometrical characteristics of the flat lid and the cylindrical body, including their flanges, on the type of the gaskets and their dimensions, and on the number, strength, and tightness of the bolts. There are well established procedures for the closure bolts design used in pressure vessels and piping. They can not be used directly in the bolts design applied to transportation packages. Prior to the use of these procedures, it is necessary consider the differences in the main loads (pressure for the pressure vessels and piping and impact loads for the transportation packages) and in the geometry (large flat lids are not used in pressure vessels and piping). So, this paper presents an approach for the design of the closure bolts of spent fuel elements transportation packages considering the impact loads and the typical geometrical configuration of the transportation packages.

1. INTRODUCTION

In general, a spent fuel transportation package has several components like an internal basket to accommodate the spent fuel to be transported, one internal and one external stainless steel cylinders connected by two flanges (internal and external) with lead located between the lateral and lower parts, an upper closure (primary lid) constituted by a shell surrounding a plate of lead, located on the internal flange. The lead constitutes the biological shield against the radiation. There is, also, a plate connected to the external flange by bolts to fix the upper closure (secondary lid). The lids are connected to the flanges by closure bolts that are the concern of this paper.

The bolted c1osure can be a weak link in the containment system of a transportation package for spent fuels. The structural integrity and leak-proof qualities of the bolted closure depend on the number, strength, and tightness of the closure bolts. For the safe performance of transportation packages, appropriate methods and criteria shall be developed for the design and analysis of their bolted closure joints.

Existing studies and industrial codes [1]-[4] focus on bolted structural joints, piping joints, and pressure vessel joints which have quite different designs and loadings from transportation package bolted closure joints.

A transportation package must be designed for significant fire and impact loads and generally has a large, flat, closure lid where no established standard exists for the design and analysis of its bolted closure.

For example, Appendix XII (Design Considerations for Bolted Flange Connections) of the ASME (American Society of mechanical Engineers) Boiler and Pressure Vessel Code, Section III [4] 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 transportation packages. In addition to high temperatures and large closure, closure bolts in transportation packages may experience severe axial and transverse impact loads.

In view of the need for a specific stress analysis method for the closure bolts of transportation packages, 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 transportation packages.

The radioactive materials transportation is regulated by guides and standards like [5] and [6]. The main purpose of these regulations is to protect persons, property and the environment from the effects of radiation during the transport of radioactive material. This protection is achieved by requiring the containment of the radioactive contents, the control of external radiation levels, the prevention of criticality, and the prevention of damage caused by heat.

Based on the applied standard, nuclear research reactors spent fuel elements transportation packages need qualification, which involves the evaluation of some conditions in a given sequence that simulates possible accidents. So, for its qualification, after the sequence of simulated conditions, the package should maintain its safety functions through its structural and functional integrity. This is achieved if, in any condition, there is the containment of the radioactive products inside it, the integrity of its biological shielding and assurance against criticality of the fuel elements.

According to [5] and [6], the transportation packages must be structurally qualified for the normal conditions of transport and the hypothetical accident conditions which are critical in relation to the package mechanical sizing. It must be demonstrated that the package has to be sturdy enough to resist:

- A drop onto a rigid target so as to suffer maximum damage, and the height of the drop measured from the lowest point of the package to the upper surface of the target shall be 9 m;
- A puncture resultant from drop so as to suffer maximum damage onto a bar rigidly mounted perpendicularly on a rigid target. The height of the drop measured from the intended point of impact of the package to the upper surface of the bar shall be 1 m and the bar shall be of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used. The upper end of the bar shall be flat and horizontal with its edge rounded off to a radius of not more than 6 mm;
- A fire resulting in a temperature of 800 °C for 30 min;
- A submersion to a 200 m depth of water.

Under the most unfavorable conditions there are strict limits on the permissible leakage of radioactive material through the containment system of the transportation package. To meet the leakage limits, all components of the bolted joint, which consist of the package 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 leak-tight quality of the joint would depend on the selection of bolt preload and gaskets.

To describe the proposed approach in detail, the paper presents its application to a half scale model of a transportation package for research reactors spent fuel that is under study in the International Atomic Energy Agency (IAEA) Latin American Project on Engineering of Casks for the Transport of Spent Fuel from Research Reactors (RLA/4/021).

2. CLOSURE BOLTS LOADS

The bolt loads result from the different loads applied to the package and also to the bolted connection. The main package loads are those generated by the internal pressure and the impacts.

To keep the closure joint integrity and leak-tightness the bolts are loaded initially with a preload in order to compensate the package loads. So, in a simplified assumption

$$F = (F_{impact1} + F_{impact2} + F_{pressure} + F_{temperature} + F_{gasket})/n \qquad (1)$$

where F is the bolt tensile axial force, $F_{impact1}$ is the force resulting from the package lid mass under the free drop impact, $F_{impact2}$ is the force resulting from the package internals mass under the free drop impact, $F_{pressure}$ is the force resulting from internal pressure, $F_{temperature}$ is the force generated by dissimilar material under temperature changes, F_{gasket} is the force to seat the gaskets, and n is the number of bolts.

The bolt preload force evaluation is the first step in the bolt sizing. Having the preload force, the selected bolt material and the available space and arrangement, the bolt cross section area and the number of bolts are determined. It is also defined the bolt length engagement in the package flange.

Generally, the package bolts preloading is performed with a torque wrench where the bolt are 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 in 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 relation is used to relate the applied torque to the achieved preload according to Eq. (2).

$$T = F \cdot \left(\frac{P}{2\pi} + \frac{\mu_t R_t}{\cos\beta} + \mu_n R_n \right) \tag{2}$$

where T is the torque, F is the bolt load (preload), P is the thread pitch, μ_t is the coefficient of friction on the thread flank, R_t is the radius of the thread flank, μ_n is the coefficient of friction at the bearing surface of the turned element, R_n is the radius of the nut-bearing surface, β is the thread flank angle (degrees) divided by 2, usually 30°.

The expression of Eq. (2) can be reduced to a more simplified one as shown in Eq. (3).

$$T = K \bullet D \bullet F \tag{3}$$

where T is the torque, K is the nut factor, D is the bolt nominal diameter, and F is the bolt force (preload). K depends on the coefficients of friction and on the bolt thread geometry. Typical values for K are 0,2 for as-received alloy or mild steel bolts and 0,3 for as-received stainless steel bolts [7].

The stress criteria for the bolts stress analysis follow the recommendations set forth in [4] and are indicated in Tab.1, where S_y and S_u are the yielding limit and ultimate limit, respectively.

Table 1. Stress criteria for the bolts closure stress analysis

Load Condition	Stress limit
Normal conditions	Average stress < 1/3 S_y
Accidental conditions	Average stress < the smaller of 0,7 S_u and S_y

3. THE HALF SCALE MODEL OF THE TRANSPORTATION PACKAGE

In this paper the closure bolts assessment is performed for the primary joint connection of a transportation package half scale model. Figure 1 shows a cross section of it.

There are two shock absorbers, each one surrounded by a thin stainless steel shell. They are connected by four round bars, and are constituted by Oriented Strand Board (OSB) glued plates. Usually, the OSB, a kind of composite or reconstituted wood, has an orthotropic behavior.

The external cylinder has a diameter of ~ 0.50m and it is ~ 0.60m high. With the shock absorbers the package overall dimensions are: external diameter ~ 0.90m and ~ 1.00m high.

In the primary bolted joint connection there are 24 bolts M12X17,5 built with the material SA-193 B8M (yielding limit S_y = 650 MPa and ultimate limit S_u = 753 MPa).

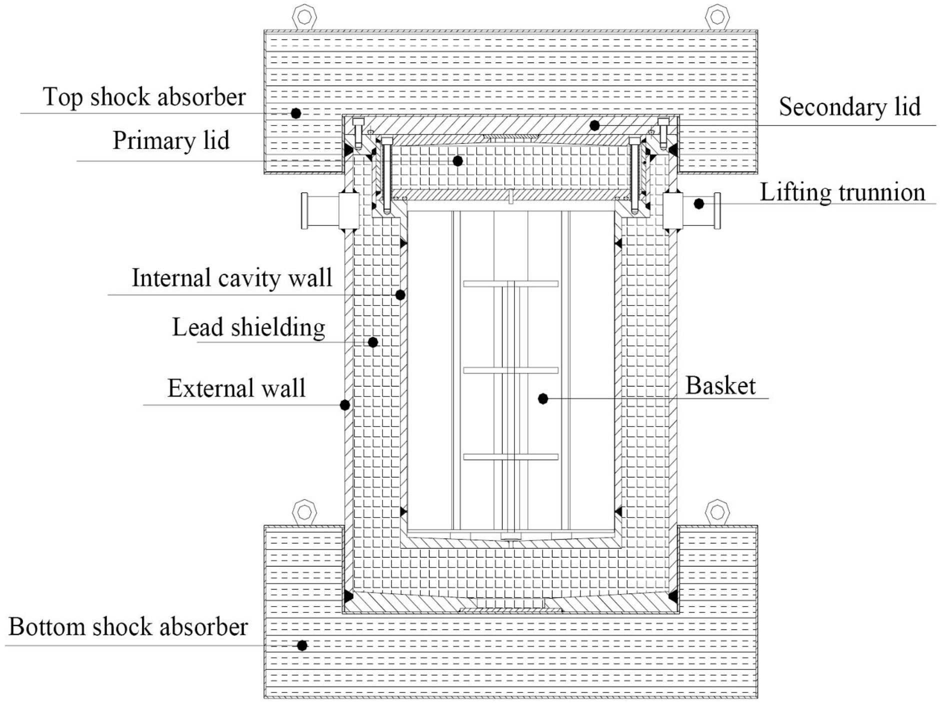

Figure 1. Cross section of the half scale model of the package

Figures 2 and 3 show, respectively, an internal view of the half scale model of the package and the bottom shock absorber partially assembled.

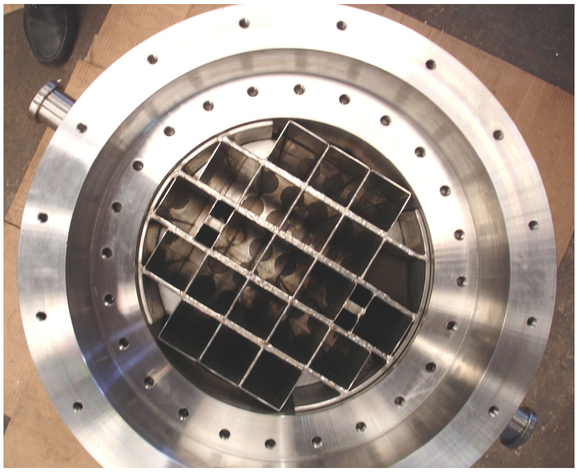

Figure 2. Internal view of the package half scale model

Figure 3. Bottom shock absorber partial assembling

4. THE HALF SCALE MODEL CLOSURE BOLTS ASSESSMENT

For the case of the transportation package half scale model under evaluation the main data for the closure bolts assessment are presented in Tab. 2. It is important to notice that the most critical condition for the closure bolts is identified as the 9 m corner drop according to [8].

Table 2: Main data for the transportation package half scale model closure bolts assessment

Data	Value
Lid mass	107 kg
Internals mass	70 kg
Maximum deceleration (9 m corner drop)	270 g ~ 2.700 m/s^2
$F_{pressure}$	65.000 N
F_{gasket}	~ 0 (the gasket is very soft)
$F_{temperature}$	~ 0 (no dissimilar materials)
Nut factor (K)	0,3 (as-received stainless steel)
Bolt nominal diameter	12 mm

The force resulting from the package lid mass under the free drop impact is given by the product 107(kg)•2.700(m/s$^{2)}$, so $F_{impact1}$=288.900 N. The force resulting from the package internals mass under the free drop impact is given by the product 70(kg)•2.700(m/s$^{2)}$, so $F_{impact2}$=189.000 N. thus, the bolt preload F=(288.900+189.000+65.000)/24=22.621 N.

Although in the bolt preload calculation the impact forces resulting from accidental 9m free drop are included, this load condition is a normal condition and the stress limit is 1/3 S_y.

The average stress in the bolt force over the bolt cross section area A $((\pi/4)\cdot D^2=113\ mm^2)$. Thus, F/A= 22.621/113=200 MPa < 1/3 S_y = (1/3) 650 = 217 MPa

The required torque to assure the bolt preload is given by Eq. (3) resulting in T=22.621•12•0,3=81.435 N mm ~ 81,5 N m.

5. CONSIDERATIONS ON THE TORQUING APPLICATION

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 [2].

This large uncertainty in the preload should be properly considered in the selection of the preload and the stress limits for the closure bolts. There are more accurate methods to apply the preloading but less convenient to use to use than the torque wrench.

Many factors combine to affect the amount of bolt load produced by torquing. These factors include the following:

- Lubrication
- Surfaces lubricated
- Flange and nut surface condition
- Presence of washers
- Thread condition
- Fastener geometry
- Reuse of bolts and nuts
- Type of lubricant

As one can see, almost all the factors are related to the coefficients of friction and affect directly the nut factor determination.

The use of lubricants is strongly recommended to improve the control on the coefficients of friction and to reduce the nut factor values.

Another important point is to establish a torquing procedure to obtain a leak-tightened bolted joint connection covering the following:

- The condition of the working surfaces
- The alignment of the mating surfaces
- The installation of the gaskets
- The lubrication of the working surfaces
- The installation of the bolts
- The numbering of the bolts
- The tightening method and the bolt load control
- The tightening sequence

The reference [9] gives the guidance on how to manage adequately the mentioned aspects.

As an example of the recommendations given in [9] one can see below the instructions to the tightening sequence.

First, the cross-pattern tensioning (star pattern) is used to maintain a relatively uniform load on the gasket (see Fig. 4).

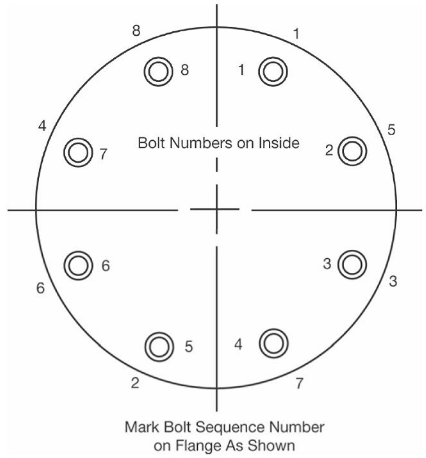

Figure 4. Recommended Bolt Tensioning Sequences

Then, it is important to gradually increase the bolt load over several passes. If too high a percentage of the final torque is applied on the first pass, the gasket can become distorted. The minimum number of passes should be a function of the applied preload. If the bolt preload stress is ≤ 52.5 ksi (362 MPa), it is suggested that the torque be applied in three passes at 33%, 67%, and 100% of the final torque for noncritical or problem joints. If the bolt preload is > 52.5 ksi (362 MPa) or is for critical or problem joints, it is suggested that the torque be applied in four passes of 25%, 50%, 75%, and 100% of final torque.

It should not be necessary to use more than four passes or to resort to complex procedures such as over-torquing the bolts, relaxing them, and re-torquing to the final torque or removing fasteners, re-lubricating them, and re-torquing to the final torque. If a high enough preload is specified and the torques are increased in several passes, the gaskets should be seated metal-to-metal without the need for these additional, time-consuming operations.

After the final pass at 100% of the specified torque is completed, the bolts will have different loads. This torque might be too low to ensure metal-to-metal contact. In all cases, leveling passes at the final torque should be applied to all of the bolts. Leveling has the beneficial effects of making the individual bolt torques more similar and increasing the overall bolt load on the gasket. If the leveling pass is not done, the joint will self-level—that is, the stresses will tend to even out and the final preload value will be substantially below the target value. The recommendation is to wait 4 hours or longer and repeat the rotational pattern to 100% target torque until no movement.

6. CONCLUSIONS

The paper shows an approach to the assessment of closure bolts used in spent fuel transportation packages

The critical loads to define the bolt preload are identified, including the package accidental conditions like the 9 m free drops. Also, the 9m free corner drop is defined as the sizing load for primary bolt lids evaluation.

It is also indicated how to determine the target torque considering that the tightening method is the torque wrench. The importance to establish a torquing procedure is emphasized.

The proposed methodology is applied to a half scale model of a fuel element transportation package with acceptable results.

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