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French requirements for the design, manufacture and use of bolts and screws equipping packages for the transport and storage of radioactive material

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ABSTRACT

In order to guarantee the behaviour of components important for safety in all conditions of transport, a specific attention should be paid on the bolted flange and screwed assemblies.

In this regard, The French nuclear safety authority for defense activities (ASND) and its technical support, the Institute for radiation protection and nuclear safety (IRSN), initiated a working group to identify good practices related to:

- the design of screwed assemblies by specifying allowable criteria in all conditions of transport;
- the representativeness of screwed components equipping mock-ups or specimens used during drop tests in terms of mechanical properties, dimensions and screws preload;
- the hypothesis considered to model, by numerical calculations, the mechanical behavior of the screws;
- the manufacturing process to prevent notably the risk of hydrogen embrittlement and the supplying controls to check the as-built properties of the screws;
- the instructions for use by listing good practices (star or cross order, time to reach the thermal steady state of the components, markings …).

The conclusions of this working group, taking into account transport events feedback and involving the main French applicants (CEA and ORANO TN), will be introduced in a dedicated guidance supported by ASND. The guidance aims at ensuring a high safety level of the radioactive material transportation.

INTRODUCTION

Integrity of packages safety functions shall be justified after the regulatory tests specified in the IAEA requirements [1]. The screwed assemblies are highly involved in many safety functions including radiological shielding, containment of radioactive materials within the package cavity, the sub-criticality of the package and dissipation of thermal power through bolted thermal conductors.

A significant number of transport events declared to the French nuclear authorities involved bolted connections. As for example :

- brittle fracture of high quality class screws ;
- poor lubrication ;
- incorrect tightening.

The number and the frequency of these events have led the French nuclear safety authority for defense activities (ASND) and the Institute for radiation protection and nuclear safety (IRSN) to initiate a working group bringing together the French main applicants (CEA and ORANO TN).
This work resulted in a dedicated guidance supported by ASND.

The aim of this guidance is to provide a technical support to designers and operators of packages by treating the safety issues which can be raised about the screwed assemblies in the different phases of their life, from design and modeling to manufacturing and use. The requirements are specified in order to ensure a high safety level for the radioactive material transportation and enhance the assessments of the package design safety report (PDSR).

FRAMEWORK

The requirements for a screwed assembly depend on its safety function.
In a first approach, the guidance focuses on screws that perform safety functions such as a containment function (lid, plug, plate), criticality or shielding and those that help to perform a safety function, such as the screws of the shock absorbers and those used to fix trunnions.
This guide only deals with the screwed assemblies made of carbon steel, alloy steel and stainless steel.

DESIGN CRITERIA

Design of screwed assemblies is guided by a standard framework. Thus, design should be performed considering the requirements of the applicable standards and calculation codes. A non-exhaustive list of documents describing a method for designing screwed assemblies is presented in references [2] to [4].

Basically, standards and codes consider some design assumptions:

- thread must be long enough in order to be stronger than the non-threaded part of the screw;
- a screwed assembly that includes a washer must be designed in order to avoid any bending of the washer which can increase stress under the washer and therefore damage the bearing surface (diameter of the screw head must be greater than diameter of the screw hole);

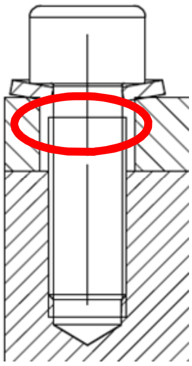

Figure 1. Bending washer

- risk of shearing the bolt must be avoid by design (radial backlash, mechanical pins).

The design criteria depend on the different transport conditions generating the mechanical and thermal stress undergone by the package.
Design of screwed assemblies in routine conditions of transport should be justified considering the following points :

- the maximum tightening stress should be less than 90 % of the yield strength for the screw at the tightening (i.e. at the ambient room temperature);
- the minimum tightening stress should guarantee on the one hand contact in assembled components under externally applied load, on the other hand, self-loosening of the screw. In fact, one on the main reason for a screw self-loosening is an insufficient pre-load [5].

For screws with low tightening (large screws with low torque, such as impact limiters screws), adaptation of design to prevent self-loosening may be interesting in the design phase (in order to reduce bolts self-loosening, the use of long bolts with a small diameter and fine-pitch threads is suggested.).

The design of the screwed assemblies useful for containment should avoid any plastic strain in all conditions of transport. Indeed, any deformation of the screws of gaskets involved in containment must be avoided in order to prevent leakage of the package. In accidental conditions of transport, in some specific cases, a limited plastic strain could be acceptable if the pre-load is sufficient to maintain the tightness of the containment seals.
In all cases, pre-load should not be exceeded in routine conditions of transport and the screwed assembly should remain in elastic strain range under normal conditions of transport.

NUMERICAL MODELING METHODS OF SCREWED ASSEMBLIES

The study of the behaviour of the screws can be done by considering different approaches as presented below:

- non modeled screw;
- screw modeled with rigid elements;
- screw modeled with beam elements;
- screw modeled in volume using deformable elements.

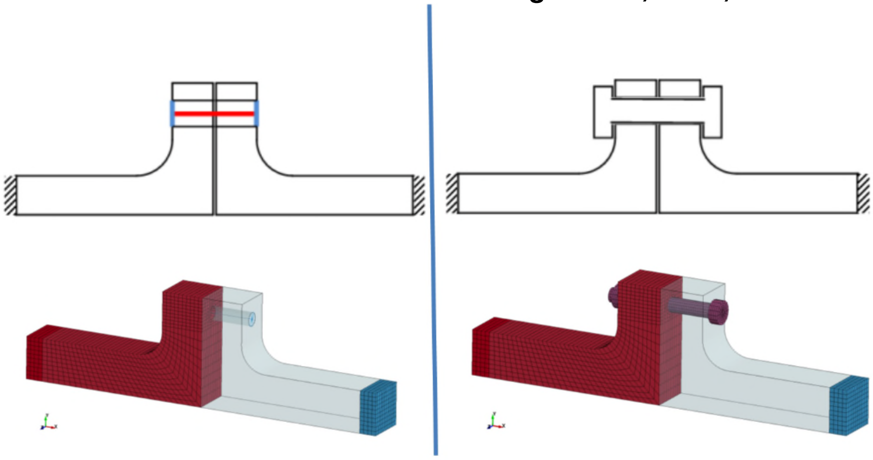

Figure 2. Screw modeled with a beam element (on the left) and screw modeled using deformable elements (on the right)

It is recommended to adopt a graduated approach, from the less accurate and the less expensive calculation time method (screw not modeled) to the most accurate and thus the most time consuming method (modeled screw by volumic finite elements). The choice should be made depending on the margins obtained on the screw and kind of mechanical solicitations.
It is recommended to justify the relevancy of chosen model based on tests results or benchmarks performed with similar screws.

The first two methods (non modelled screw and screw modelled with rigid elements) don't take into account the screw itself, thus rigidity and preload are not considered as well. These methods are efficient but unrealistic in terms of relative movement of assembled parts. In addition, they do not make it possible to evaluate the tightness of the screwed assembly studied. It is therefore recommended to use these methods when the safety issue are limited or in case of very high design margins.

Concerning the screws modelled with beam elements, it is not recommended to use this method when the screw is highly stressed in shear or bending. In this respect, when this method is chosen, mechanical stress applied on the screw should be clearly identified.

Therefore, this method is not the suitable method to model the containment screws. However, it is acceptable to use it in the following cases:

- the screw is not stressed in shear or bending;
- the diameter of the screw is small and make it difficult to model by solid elements;
- there are significant design margins.

In any case, the geometrical characteristics of the model used should be detailed and justified, such as the number of elements modeled and the mechanical linkages applied at the ends of the beam.

The modeling of the screws by a solid model based on deformable solid elements is the method that best reproduces the different kind of stress undergone by the screw in the different conditions of transport. Indeed, it makes it possible to appreciate the phenomena of bending and shearing in the screw as well as the potential separation of the assembled parts. Nevertheless, this method has the disadvantage of requiring a high calculation time. It should be justified that the mesh used allows to correctly represent the state of stress in the screw. For example, sensitivity calculations have shown that the variation of the mesh size could lead to an increase in the equivalent stress in the screw. Moreover, one must pay a particular attention to the post-processing used to determine the maximum equivalent stress in the screws in order to ensure that the results are conservative.

REPRESENTATIVENESS OF SCREWED ASSEMBLIES EQUIPPING MOCK-UPS AND TEST SPECIMEN

In order to justify the integrity of the package safety functions in all conditions of transport, the applicants perform drop tests. Using mock-ups or test specimens at reduce or real scale, drop tests simulating the mechanical behaviour of package are often completed with numerical calculations to evaluate, for example, the behaviour at higher temperature.

In this framework, it should be demonstrated that the properties of the screws equipping the specimen are more penalizing than the technical specifications of the screws intended for the package. In this respect, it is necessary to choose the penalizing parameters taken into account (height of drop test, geometric dimensions of the screw, mechanical properties, tightening conditions).

The demonstration could also be based on numerical calculations. In this context, one or several qualifying drop tests can be performed in order to validate the results obtained with a numerical model of the package. In this case, it may not be necessary to demonstrate that the screwed assemblies equipping the specimen are penalizing compared to the screwed assemblies provided for the real package. Nevertheless, it is recommended to know precisely the mechanical and dimensional characteristics as well as the tightening conditions of the screws used in order to be able to validate the numerical model developed to simulate the drop tests. One has to note that the more tests are calculated, the more uncertainties are low.

BRITTLE FRACTURE

Brittle fracture of the screws can occur due to Internal Hydrogen Embrittlement (IHE). IHE is a permanent loss of ductility caused by residual hydrogen involved by steelmaking or processing steps such as pickling and electroplating. The reasons these processes are significant is that they are the final manufacturing steps and that the coating materials act as a barrier to hydrogen effusion. In other words, the coating prevents hydrogen’s natural tendency to diffuse out of the steel at room temperature.

Failures due to IHE can occur in the hours that follow the set-up of the screws. Thus, failure can occur in a time scale corresponding to the usual duration of a transport of radioactive material on the public road. This kind of issue has been raised in Japan as well [6].

Three conditions must meet to cause hydrogen embrittlement failure: steel that is sensitive to hydrogen damage, stress (pre-load in case of screws) and hydrogen. If all three of these elements are present in sufficient quantities, hydrogen damage results in crack initiation and growth until the occurrence of failure. It has been noticed that 12.9 property class screws and above have significant sensitivity to IHE. Concerning 10.9 quality class screws, precautions should be taken. Thus, screws with property class less or equal to 9.8 should be preferably used. Otherwise, caution should be taken during processing in order to limit the hydrogen embrittlement risk. Based on the complexity of the phenomena involved during the manufacturing process and the lack of feedback concerning the qualification of the manufacturing process of 14.9 property class screws with respect to the embrittlement risk, it is recommended to avoid the use of screws with property classes greater than or equal to 14.9.

As it was written above, acid pickling is a significant source of hydrogen before coating processes. Therefore, it is recommended to prohibit acid pickling for screws of property class above 10.9. Concerning 10.9 quality class screws, precautions should be taken. For example, an appropriate inhibitor should be used and a minimum cycle time should be provided for cleaning to reduce the risk of hydrogen embrittlement.

When the screw is coated by galvanic processes, the common practice to limit the risk of IHE is to heat at low temperature the screw after the coating process in order to extract any diffusible hydrogen that was introduced during the manufacturing process. Baking is necessary for screws of 12.9 quality class and above.
Additional verification of the manufacturing process or hydrogen embrittlement test methods are required depending on the quality class of the screw. The French standard NF EN ISO 4042 in reference [7] recommends specifications on electroplated coatings sum up in the table 1 hereafter.

Table 1. Requirements depending on the quality class and the Vickers hardness of the screw

Property class	≤ 9.8	10.9	12.9
Vickers Hardness	< 360 HV	360 HV ≤ Hardness ≤ 390 HV	> 390 HV
Specifications	Additional verification of the manufactural process or hydrogen embrittlement test methods **AND** No necessary baking	Additional verification of the manufactural process or hydrogen embrittlement test methods **OR** Baking	Additional verification of the manufactural process or hydrogen embrittlement test methods **AND** Baking

Zinc lamellar coatings are not concerned by the risk of hydrogen embrittlement and allow a good corrosion protection. These coatings are non-electrolytically applied and composed of a mixture of zinc and aluminium flakes which are bonded together. Nevertheless, in the same way as for electrolytic coatings, it is recommended to prohibit acid pickling for quality class screws above 10.9.

LUBRICATION OF THE SCREWS

Friction coefficients of the screw depend on the kind of lubricant applied. Generally, lubricant is applied at two different places: under the screw head and on the threaded part of the screw. IRSN’s feedback shows that it is usually difficult to demonstrate that in case of thread lubrication, there is no lubricant under screw head because of the small space between the screw and the parts to assemble. Lubricant under head of a bolt will decrease the friction

coefficient and consequently increase the applied load for same torque applied. Such an increase could result in overstress in the screws [8].
Thus, it is recommended to apply lubricant both on the threads and under the screw head. In addition, the type of lubricant used must be consistent with the friction coefficients considered in the design calculations.

SELF-LOOSENING OF FASTENING SCREWS

Over the last 7 years, around twenty five events were declared in France after the observation, during the package unloading operations, that some of these screws could be loosened by hand.
Following these events, some packages designers and shippers have implemented enhanced controls of tightening operations by checklists to be completed by the operators (check of the localization of the lubricant on the screws external surfaces, observance of the waiting period until thermal steady state, observance of the tightening star or cross order usually recommended for all package designs and check of the applied tightening torque) in order to limit the risk of self-loosening of the screws [5]. These operations constitute good practices and allow to prevent from human errors and self-loosening of the screws.

Figure 3. Tightening cross order

Moreover, particularly for the screws that perform a containment or a criticality prevention function (when the hypothesis taken into account is a limited water penetration into the cavity), it is recommended to check screw tightening before shipment by another operator from the one who performed the tightening. These operators have to use two different tools.

SCREWS DO NOT COMPLY WITH THE PDSR

Screws may be similar in their geometrical characteristics (length, thread) but differ in their mechanical characteristics (different property class) or their coatings (it can change the friction coefficient) which can induce mechanical issues during shipment. Some issues can also occur because of the important number of screws which can be removed during the loading and unloading of the package as well as during the maintenance of the package.
It is recommended that the design of packages allows to distinguish the screws when they have similar characteristics. It is also recommended to ensure the traceability of the fasteners (marking of the quality class, the supplier logo or the batch number) and implement method for identifying screws (color code to associate the screws to the components to fix or specific storage racks for example).

CONCLUSION

The aim of the working group initiated by the French nuclear authority for defense activities (ASND) was to identify general requirements applied to the screwed assemblies ensuring a safety function of package designs. This work, involving the Institute for radiation protection and nuclear safety (IRSN) and the main French applicants (ORANO and CEA), has been performed considering standards and feedback learned from assessments, use and manufacture of package designs developed in France since several decades.
In this framework, different subjects have been discussed to identify provisions concerning notably:

- the design of the screwed or bolted connections
- their representativeness during drop tests when demonstrations are based on mock-up or specimen behaviour,
- hypothesis considered in numerical calculations to model the mechanical behaviour of screwed connections;
- the screw manufacturing including specifications like heat and surface treatment, supply, traceability and controls;
- good practices to consider during the package loading operations for the tightening operations.

Conclusions of this working group led to identify several recommendations which have been included in a dedicated guidance established under the aegis of the ASND.

The use of this guidance will on the one hand improve the completeness of the safety demonstrations transmitted by applicants in support to their approval request for package designs and on the other hand facilitate technical assessment.

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