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ISO-STANDARD AND IAEA GUIDANCE MATERIAL FOR PACKAGE LOAD ATTACHMENT POINTS – Current Approaches and Developments

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ABSTRACT

For transport package design and operation according to the IAEA regulations, the package shall be securely stowed and its retention system shall be capable to withstand load conditions of routine transport. The supporting IAEA Advisory Material SSG-26 provides information how to do that.
Up to now package designers in different countries use other load factors for the design of attachment points than those specified in the IAEA guidance material. In particular the acceleration values vary between different countries and lead to difficulties during the validation of foreign approval certificates. Therefore the IAEA started a discussion process to review the existing guidance text. An international working group was constituted in 2013. Representatives came from different stakeholders, e.g. transport operators, competent authorities and modal organizations. The discussions concluded especially on the transport conditions which has to be considered for stowage design, including on the one hand the relevance of the load factors used for strength and fatigue analysis and on the other hand the criteria which have to be considered for the attachment points.
The proposed acceleration values will be compared to those measured during recent multi-modal testing by Sandia National Laboratories that measured the acceleration levels experienced by a spent fuel flask during heavy-haul truck, sea, and rail transport.
The ISO standard 10276 is dealing with the load attachment systems of packages as well. This standard considers the trunnion design, manufacturing and operational aspects. The regular standard revision phase started in 2017. An expert group discussed new state-of-the-art technology, different analysis approaches for strength and fatigue analysis and proposed revised text for the ISO standard for international discussion. The finite-element analysis approach incl. appropriate acceptance criteria are described and referenced.
The paper describes relevant tie-down aspects, gives background argumentation relevant to analysis approaches, and tries to support harmonized application of the revised IAEA guidance material and the future revised ISO standard.

INTRODUCTION

The design evaluation of load attachment of packages for the transport of radioactive material is part of the package approval procedure. The loads and design approaches should be accepted as state-of-the-art technology and for worldwide used packages acceptable for the competent authorities involved.
The IAEA started a technical review on the existing guidance material for package stowage and retention in 2013. The Transport Safety Standard Committee (TRANSSC) established an international expert group for technical discussion and preparing up-to-date guidance text.
It was agreed the existing transport acceleration values in IAEA Advisory Material SSG-26 [2] were not realistically applicable. The entire guidance text was reviewed by the international experts.

During several meetings of the consultants the harmonization of design requirements incl. acceleration values and good practice approaches for load attachment points were in focus.
After the group could provide revised text of the Appendix IV of the Guidance Material SSG-26 [2] the existing ISO standard 10276 [3] was under review by ISO TC85/SC5/WG4.
It was agreed among the participating ISO members that a complete re-writing the standard should be done. Links to international regulations, e.g., the IAEA regulations SSR-6 [1], and international guidelines, e.g., IAEA Advisory Material SSG-26 [2] and BAM-GGR 012 [6] should be considered.

Figure 1: Transport of a Heavy Weight Package TN85, ©photo by Daher DNT

NEW IAEA GUIDANCE MATERIAL

Several topics were discussed among the international expert group built up of competent authorities, technical support organizations, and transport stakeholders. For example, some discussions focused on the conditions which have to be considered for stowage design, both as relevant to the load (acceleration) factors used for strength and fatigue analysis, as well as the criteria which have to be considered for the package attachment points. In addition, related questions on operational aspects were also discussed. The history of the work done by the IAEA consultant group is summarized by Moutarde in [13].
As a result, the international working group produced new guidance material for stowage in transport, addressing each of these topics. The proposal to modify the IAEA Advisory Material SSG-26 [2], Appendix IV, presented by France to the IAEA TRANSSC in the 2015 initiated review cycle of the Regulations, was unanimously accepted and will be implemented in the next edition of the guidance material.
The revised Appendix IV of IAEA SSG-26 [2] provides guidance on considering the effects of the tie-down system loads applied to the package during routine conditions of transport. It describes possible methods for demonstrating compliance with package design requirements. Attachment points are integral parts of the package. All other parts of the retention (tie-down) system such as tie-down members (e.g. lashings, ropes, chains or straps), anchor points, chocks, etc., which are not part of the package, are addressed by modal and national requirements.
The inertial forces that act on the packages during routine conditions of transport may be caused by, for example: uneven road or track, vibration, braking and accelerations, direction changes, rail shunting (when permitted), motions of a ship in heavy seas and turbulence in air transport.
Package retention systems shall be designed to perform in a predictable manner under all conditions of transport. However, in normal or accident conditions of transport, the package is permitted, and may be required as part of the design, to separate from the conveyance by the breakage or designed release of its restraint in order to preserve package integrity.
The new guidance does not focus on handling loads. However, when an attachment point is used both for lifting and tie-down then the lifting operation loads, including snatch lifting loads, should be taken into account in the design. Some examples are mentioned in the new revision of DIN ISO 10276 [3].

Demonstrating compliance through analysis

Structural analysis of attachment points under routine conditions of transport should include strength analysis and fatigue analysis of relevant components. If necessary, issues such as brittle fracture and structural stability should be considered. The temperature range of the attachment points under routine conditions of transport should be taken into account.

Structural analysis of attachment points can generally be performed by analytical methods, e.g. beam theory, or by extended numerical methods. The interpretation of the results depends upon the assessment technique (e.g. nominal stress, local stress or stress linearization). Basically, the package, including its attachment points, shall not be stressed beyond yield in routine conditions of transport.

Applicable analysis methods, assessment techniques and design criteria should be acceptable to the relevant competent authorities. Examples of various approaches are given in ISO 10276 [3] and BAM-GGR 012 [6]. Guidelines are also provided by [14].

Owing to the differences in transport infrastructures and practices, the national competent authorities and the national and international transport modal standards and regulations need to be consulted to confirm the mandatory or recommended package loads, together with any special conditions for transport, which should be used in the design of the packages. These loads are generally specified by acceleration values to represent the package inertial effects for structural analysis, and are usually applied at the package centre of gravity as equivalent quasi-static forces. The load case data may differ according to the type of structural analysis (strength analysis or fatigue analysis).

If the design has more than two attachment points then load sharing between them should be considered carefully.

For strength analysis the acceleration values representing routine conditions of transport are presented in Table 1. The values are derived from different national and international standards and guidelines, using a factor of about 1.25 to increase the confidence that the proposed range of loading will not be exceeded.

If a specific design code is used in the analysis, an additional safety factor consistent with the applied code may be required. If no specific design code is used, then a safety factor should be considered and justified in the analysis. The forces imposed on the package are determined by multiplying the acceleration values listed in Table 1 by the mass of the package and are applied at its centre of gravity. The analysis should first consider application of each directional acceleration value separately and then all combinations for each line in Table 1 for the relevant transport mode.

In addition to strength analysis, the package designer should also account for the effects of cyclic loads under routine conditions of transport which could lead to the failure of components of the package. For fatigue analysis, it is preferable to design the attachment point for infinite endurance but, as an alternative, it is also acceptable to determine the fatigue life of the attachment point and to control it in service. A detailed fatigue analysis may not be necessary if the number of load cycles applied to the attachment point do not exceed a threshold specified in the relevant design code. Acceleration values for fatigue analysis DIN EN 12663 [7] imparted by rail wagons are reproduced in Figure 2. The use of these values is possible if the conditions and criteria of the standard DIN EN 12663 [7] are relevant. Other acceleration values for fatigue analysis for different transport modes can be found in TSCS 1006 [8]. If the data in the reference are not applicable, appropriate measurement data should be provided by the package designer. Acceleration values, number of cycles, allowable stress levels and acceptable design criteria for fatigue assessment should be agreed with the relevant competent authorities. For attachment points that are also used for lifting, the lifting cycles should be included in the fatigue analysis.

Inspection and maintenance are necessary and should be specified by the designer over life time of the package and the load attachment point. It should be pointed out that fatigue analysis is not a substitute for inspection and maintenance.

Mode	Longitudinal	Lateral	Vertical [a]
Road	1g	-	1g down ± 0.3g [b]
	-	0.7g	1g down ± 0.3g [b]
Rail	1.3g/5g [c]		1g down ± 0.4g
		0.7g	1g down ± 0.4g
Sea/water	0.5g	-	1g down ± 1g
	0.3g	1g	1g down ± 0.6g
Air	1.3g	-	1g down
	-	1.3g	1g down
	-	-	2.5g up, 2.5g down

Table 1: Acceleration values incl. load combinations for strength analysis

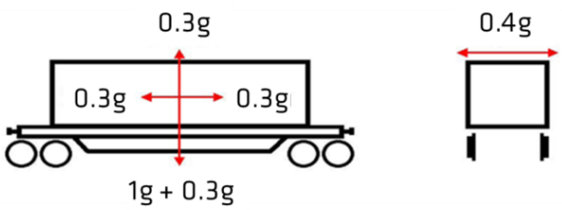

Figure 2: Acceleration values for fatigue analysis according to DIN EN 12663 [7]

MEASUREMENT CAMPAIGN BY MULTI-MODAL TRANSPORT TESTING

As mentioned above the values in Table 1 are derived from different national and international standards and guidelines. In the last years some new measurement campaigns were performed to investigate the acceleration level during the transportation, e.g. [15-18].

In 2017 a team from Sandia National Laboratories (SNL) conducted an international 8-month, 15,000-km (9,400-mile) test to simulate transportation scenarios for spent nuclear fuel (SNF). The purpose of this project was to quantify the shocks and vibrations environments during routine conditions of transport. SNL conducted this test in collaboration with Pacific Northwest National Laboratory (PNNL) and ENSA (nuclear equipment global supplier). It involved coordination with Korea Radioactive Waste Agency (KORAD) and Korea Atomic Energy Research Institute (KAERI), the Association of American Railroads (AAR), and Transportation Technology Center, Inc. (TTCI). Testing was performed using an ENSA ENUN 32P cask. As configured for this test, the cask measured 5 meters in length with a body diameter of 2.65 meters. The loaded weight of the carbon steel cask was 120 tons and 137 tons with the surrogate impact limiters.

An instrumented transportation cask containing surrogate fuel assemblies from the US, Spain and Korea was transported by truck in Spain, by barge to Belgium, by ship to Baltimore, and by rail to Colorado for rail tests at TTCI and back to Baltimore by rail. Six terabytes of data were collected over the 54-day, 7-country, 12-state, 15,000 km of travel. For the first time, strains and accelerations were measured directly on the surrogate nuclear fuel assemblies and on the basket. The accelerations were measured on the cask, cradle, and transportation platform. A total of 40 accelerometers and 37 strain gauges were used. The analysis of the transportation test data was performed in 2018 and is documented in [16] (data analysis) and [17] (modeling). A short video documenting the major test events is available on YouTube [18].

A total of 2,939 shock events were identified along the 3,100-km route from the Port of Baltimore (Maryland) to Pueblo, Colorado. The accelerations observed during the maximum acceleration event are shown in Figure 3. The accelerations on the middle of the transportation platform were 0.8g (vertical), 0.31g (longitudinal), and 0.36g (lateral). The accelerations on the cradle were 0.77g (vertical), 0.38g (longitudinal), and 0.52g (lateral). The accelerations on the cask were 0.16g (vertical), 0.13g (longitudinal), and 0.16g (lateral). The maximum vertical accelerations on the surrogate assemblies were 0.65g (SNL), 0.95g (ENSA), and 0.39g (Korean assembly).

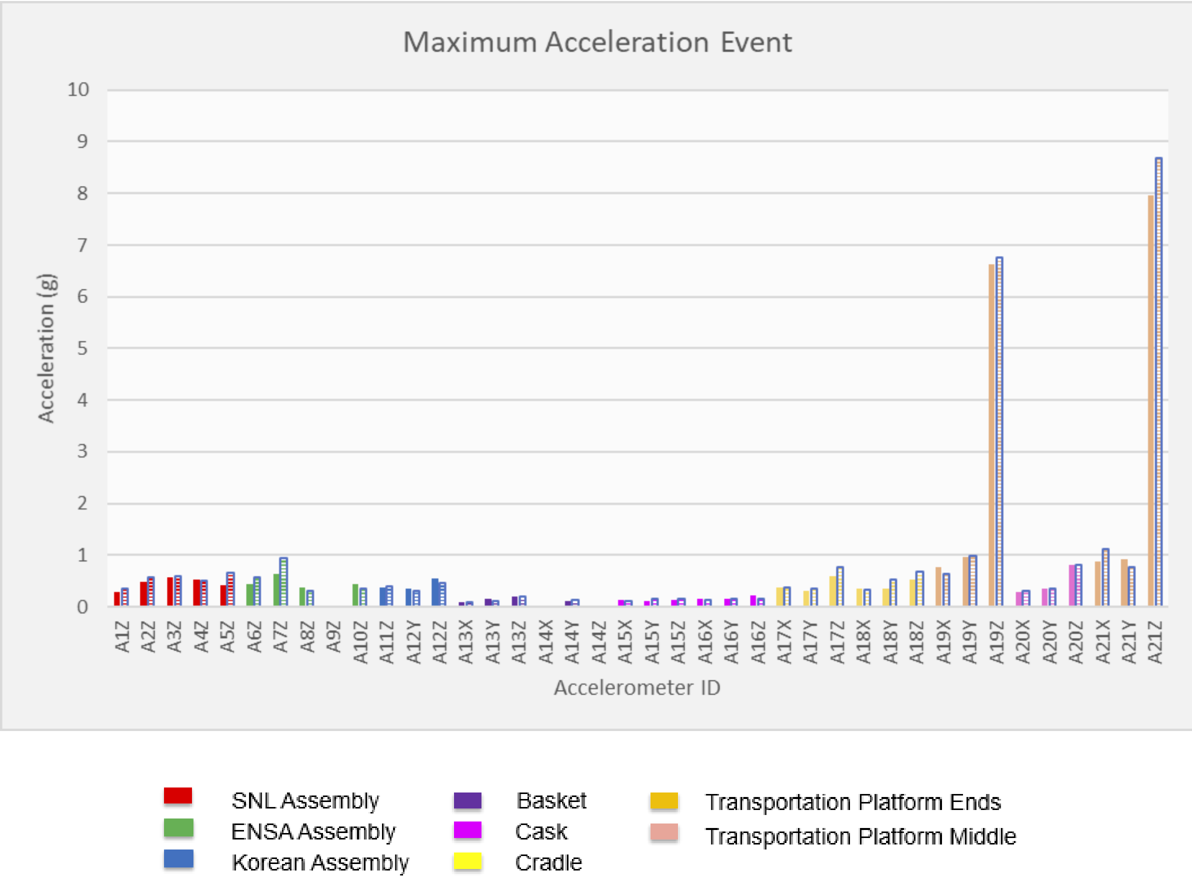

Figure 3. Rail transport accelerations observed during maximum acceleration event

Heavy-haul truck data were recorded from the ENSA facility in Maliaño, Spain via a 400 km route. A total of 36 shock events were identified. The accelerations observed during the maximum acceleration event were similar to the rail transport accelerations described above. The exception was vertical acceleration on the middle of the transportation platform of 2.18g.

The accelerations on the middle of the transportation platform were 2.18g (vertical), 0.23g (longitudinal), and 0.30 g (lateral). The accelerations on the cradle were 0.15g (vertical), 0.14g (longitudinal), and 0.18g (lateral). The accelerations on the cask were 0.20g (vertical), 0.16g (longitudinal), and 0.08g (lateral). The maximum vertical accelerations on the surrogate assemblies were 0.42g (SNL), 0.42g (ENSA), and 0.19g (Korean assembly).

The multi-modal transportation test of the ENSA ENUN 32P cask test unit included coastal shipment via barge and ocean crossing on a merchant vessel. The accelerations observed during barge and ship transport were very low (≤0.3g with a few exceptions). They are significantly lower compared to all the rail and heavy-haul transport accelerations.

REVISION OF ISO 10276 STANDARD

The current ISO 10276 [3] deals with trunnions for packages used to transport radioactive material. The existing standard is used in a few cases worldwide to design and maintain load attachment points.

The existing text provides inconsistent load data; applicable design approaches are missing. Furthermore the references given are not up-to-date.
The ISO members decided to review the existing text. Over the last years experts from France, UK, Japan and Germany discussed a new structure of the standard and did provide revised text to the ISO community for technical discussion of applicability. The focus of the standard was expanded to trunnion systems and not only to the trunnions themselves.
The main points of improvement are: a clear structure of the standard comparable to the design of other technical components, to provide commonly used and accepted load data, design approaches, maintenance requirements and a best practice guide.
The following introduces some parts of the proposed revised text of the standard and gives an overview of new approaches and updated good practices according with the work by the ISO expert group (see subchapter acknowledgments).
Trunnion systems as part of a package design shall be designed in accordance with IAEA SSR-6 [1] with consideration of IAEA SSG-26 [2]. The trunnion fastening to a packaging may be carried out by welding, bolting, interference fitting and bolting, or any combination of these methods. It is proposed this international standard will apply to these methods of trunnion fastening.

Design methodology

The proposed revised text of the standard states, like [2], that structural analysis of trunnion systems shall include a strength analysis and a fatigue analysis. If necessary, issues such as brittle fracture and structural stability should be considered too. This analysis can generally be performed by analytical methods, by finite element analysis (FEA) or by a combination thereof. As FEA leads to more detailed stress and strain results for complex structures, it may be preferred in case of trunnion systems with complex geometry or load situation.

Mechanical properties

For the selected materials, the minimum mechanical strengths $R_e(T)$ and $R_m(T)$ shall be specified.
For ferritic steels, to ensure that the material is sufficiently ductile and tough, it shall be capable of achieving the Charpy impact test energy of 27J minimum at the minimum temperature according to the IAEA transport regulations and tensile test elongation to failure of 14% minimum at 20°C.
Where trunnions are not wholly stainless steel, but are stainless-steel covered, the mechanical properties used in calculations for both the base and cladding materials shall be those of the base material.
Consideration shall be given to the hardness of the trunnion and attachment component materials to minimize any surface incompatibility that can arise due to the material hardness of interface equipment.
Fracture toughness properties, such as K_{Ic}, of the materials shall be specified if needed to enable a fracture mechanics analysis of the trunnion system.

Design loads

Assembly state: Where the trunnion attachment includes bolts, the bolt minimal ensured preload shall be appropriate to avoid any loosening of the bolts and sliding of the trunnion under the bolt heads during operation, including the effects of vibrations during transport.
Depending on the assembling method, the bolt preload can vary due to the friction values between the bolts and their contact surfaces and also due to the uncertainties of tightening techniques. The bolt preload can also be affected by different thermal expansion due to temperature change between assembly and design conditions. See reference [10] for further details.
Tie down: Designers may consider using different numbers of trunnions on packages to suit different operational or transport requirements. Where trunnions are used for tie-down, the total number of trunnions in any one plane may be restrained unequally. Consideration should be given to alignment on both the package and the tie-down equipment when four (or more) trunnions share a load. Local positioning imperfections or variations in tolerances can lead to high variations in the loads acting on each trunnion. Therefore, in absence of justification, it shall be considered that the load is supported only by two trunnions out of four.
The designer shall consider the different modes of transport the package is intended for. It is possible that the directional orientation of a package differs between different modes of transport, e.g. the

orientation of a package during sea transport may be at right angles to the orientation of the same package during rail transport. The designers shall consider all reasonably foreseeable package orientation during transport to determine the highest load case combination.
The designer shall identify all the possible allowed tie-down configurations and shall define for each the load case. Each load case shall be associated to:

— maximal load,
— load direction,
— bearing area of trunnion with transport means,
— number of acting trunnions.

The maximal load applied shall generally be the total mass (transport) multiplied by the "acceleration" factor shown in Table 1 and in associated paragraphs of Appendix IV of IAEA SSG-26 [2]. Other values may be used subjected to appropriate justification.
Lifting and/or tilting: Depending upon the design for operation, the package may have the capability of being lifted and/or tilted on the same trunnions. In some cases, packages might not be designed to be tilted. Whichever case occurs, the total mass (lifting) that applies at any time to the minimum justified number of trunnions shall be taken into account.
The guidance about load sharing and imperfection are similar if the attachment points are used for lifting and/or tilting.
The designer shall identify all the possible allowed lifting or tilting configurations and shall define for each the load case. Each load case shall be associated to:

– maximal load,
– load direction,
– bearing area of trunnion with lifting or tilting means,
– number of acting trunnions.

The maximal load applying for a given load case shall be the corresponding lifting mass multiplied by a snatch factor of 1,8g by reference to [4]. Other values may be used subject to appropriate justification, e.g. [4], [5] or [9].

Load cycles for fatigue analysis

The designer shall take into account the fact that the in-service life can be reduced due to the effects of fatigue caused by cyclic stresses during transport, lifting or a combination of both. Fatigue analysis shall consider the whole lifetime of the trunnion system with load combinations from transport and lifting and/or tilting operations.
It is not possible to define universally valid load cycles for a transport on public routes therefore they must be specified both on the basis of the requested modes of transport (road, rail, sea or air) and on the basis of the length and number of anticipated transport cycles.
In addition to experimental determination of the transport load cycles, reference may also be made to published measurements. The transfer to other packages or transport routes may necessitate the use of correction factors in the fatigue analysis. See IAEA SSG-26 [2], Appendix IV for further details.

Methods of analysis and design criteria

For all the components of the trunnion system, the maximal equivalent stress (local or if allowable linearized stress) shall not exceed the predetermined limit value.
This limit value is generally derived from correspondent $R_e(T)$ taking into account a safety factor depending on the analysis method.
Specific considerations shall be evaluated for bolted trunnions to ensure the safe assembly is justified.
An additional safety factor shall be included for welded joints/interfaces. To justify the value of the safety factors to be used, due consideration should be given to the method of welding, non-destructive examination (NDE) and management system.
More stringent safety factors may be added according some specific applicable national requirements, for instance in [4] or [5].
Examples of approaches for strength analysis of trunnion systems are given in [6] and [9].

Strength analysis using analytical methods and FEA methods

An analytical approach for strength analysis can be based for instance on [5] or [9].

In the case of trunnion systems with complex geometry and asymmetric loading situation, FEA should be preferred to an analytical approach. FEA leads to more detailed stress and strain results for complex structures. The use of FEA is recommended for strength analysis to calculate the spatial stress state at the most severely stressed points.

An approach using FEA methods for strength analysis is as follows:

- Each load case defined for tie-down, lifting or tilting configurations shall be considered.
- The stress evaluation for all components (incl. bolts) shall be based on the equivalent stress according to the Tresca criterion (max. shear stress theory) or Von Mises criterion (max distortion energy theory).
- Where the linearization of the stresses is justified, then the linearized equivalent stress at the most severely stressed point of the trunnion shall not exceed the value $R_e(T)$ / 1,5.
- The maximal equivalent local stress in the trunnion shall not exceed $R_e(T)$. Additional considerations may be necessary to show the safety margins against plastic collapse of the trunnion's cross section relevant for the load-bearing capacity, see [6] for instance.
- For trunnion attachment components:
- the maximal stresses shall be less than $R_e(T)$. Concerning stresses in the shear disk housing, other justified criteria may be used for the limiting surface pressure, see [10] for instance.

For the trunnion bolts:

- the analysis and evaluation of bolts shall be performed according to national or international recognized standard, for instance [6], [9] and [10].
- the local stresses of FEA shall be transformed into nominal ones, as recommended in guideline [6]. The maximal linearized equivalent stresses shall be less than $R_e(T)$.
- the maximal stress in the trunnion under the bolt heads shall not exceed $R_e(T)$. Other justified criteria may be used for the limiting surface pressure, see [10] for instance.

In case of complex interface between the trunnion system, the packaging body and the equipment where the physical phenomena shall be sufficiently detailed, a consideration of trunnion system instead of an isolated analysis of single structural components (trunnion, bolts, etc.) shall be done to properly include interactions between components. More detailed guidance for modelling trunnion system can be found in references [6] for instance.

Brittle fracture evaluation

Some materials are more susceptible to brittle failure at low temperatures and/or under lifting and routine conditions. In such cases, the designer shall apply an appropriate approach to avoid brittle fracture at the minimum service temperature. Guidance is given at Appendix V of IAEA SSG-26 [2].

Fatigue analysis

Fatigue analysis shall consider peak stresses, and any weakening due to welds and features that can induce stress concentrations, and appropriate fatigue curves for the material that is used.

The safety factor depends on the material properties, the calculation method and the applied load-cycle behaviour. It may also vary depending on the applicable national requirements and the consequences of failure. For example, approaches for fatigue evaluation can be found in [9] for general aspect or in [6] for lifting/tilting operations.

Other requirements and recommendations

The designer should aim to achieve simplicity and repeatability in determining the requirements for inspection, testing and assembly.

The design of the trunnion systems should, where possible, be integrated with the design of interfacing lifting equipment or, otherwise, the trunnion systems and interfacing equipment proposed should be assessed for mutual compatibility of geometry and material.

Consideration should be given to the trunnion surface finish with regards to decontaminability, tilting and fatigue analysis.

The areas requiring regular inspection are surfaces subject to damage as well as bolts and threaded holes. These areas should be easily accessible and designed to facilitate inspection. The life of a

trunnion system can be increased if repair is possible to recover non-conforming trunnions or attachments components. Consideration should be given to the inclusion of an allowance within the design criteria to enable the recovery of non-conforming items.
As-built dimensional records of each trunnion, which are part of the manufacturing record/lifetime record, should be retained as a basis for comparison during inspection.
To facilitate the evaluation of surface cracks and damage, the designer should specify that the inspection criteria incorporate a fracture mechanics based approach.
For bolted trunnions the designer should consider the bolt strength grade and any requirement for the attachment components to withstand the effects of the operational environment, for example reactor-pond water.

Quality management system

The management system shall comply with IAEA SSR-6 [1]; some guidance can be found in IAEA TS-G-1.4 [12].
To ensure the consistent quality of the processes the implementation of a quality management system based on ISO 9001:2015 [11] is advised.
Activities, processes, criteria and methods related to trunnion systems shall comply with the management system of the package design. The package designer shall define quality plans and maintenance criteria related to trunnion systems as part of the management system of the package design. Manufacture, assembly, maintenance, inspections and repair are focused in other parts of the draft of the standard as well.

CONCLUSION

Recent effort at IAEA and ISO focussed on the revision of the existing IAEA guideline and the ISO standard about package load attachment systems. After intensive discussions among international technical experts in this field, harmonized acceleration values could be derived and implemented in the draft of IAEA Guidance Material SSG-26. The ISO 10276 standard was completely re-written, references with current international approaches and examples were updated. Both documents were provided for comments and ongoing international discussions.

ACKNOWLEDGMENTS

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