



ONR GUIDE			
Criticality Safety Assessment of Transport Packages			
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1. INTRODUCTION

- 1.1 ONR has prepared a suite of technical assessment guides (TAG) to assist its inspectors in their technical assessment work in support of making regulatory judgements and decisions. The guides were originally prepared to support ONR's Safety Assessment Principles (SAPs) [1], which apply to the assessment by ONR specialist inspectors of safety cases for nuclear facilities. More recently the scope of this suite of guides has been extended to other areas of ONR's regulatory responsibility including radioactive materials transport. This TAG is one of these guides.

2. PURPOSE AND SCOPE

- 2.1 This TAG provides guidance to ONR inspectors for assessing the criticality safety of transport package designs and the adequacy of the tests carried out on packages, as described in Package Design Safety Reports (PDSRs) submitted in support of requests for design approvals.
- 2.2 The TAG is limited to the aspects of the transport regulations that ensure the criticality safety of package designs. The guidance does not extend to the other safety attributes of transport packages designs, namely those of; containment of the radioactive contents, control of the external radiation hazards and the prevention of damage caused by heat.
- 2.3 This TAG contains guidance to advise and inform ONR staff in the exercise of their regulatory judgment.

3. LEGISLATION GOVERNING THE TRANSPORT OF RADIOACTIVE MATERIALS

- 3.1 The opening sections of the Transport Permissioning Process Guide, TRA-PER-GD-001 [2], and the ONR Guidance for Applications [3] summarise the legislative framework governing the transport of radioactive materials and ONR's role, acting as a UK Competent Authority (CA). This framework is closely based on the IAEA safety requirements document, SSR-6 'Regulations for the Safe Transport of Radioactive Material' [4]. Consequently, the requirements in SSR-6, although not legally binding themselves, provide the standards against which transport PDSRs may be assessed. Clearly any formal communications with dutyholders, permissioning documentation or enforcement action being considered by ONR inspectors should make reference to the appropriate UK legal provisions for the mode of transport in question.

IAEA Regulations

- 3.2 The IAEA Regulations apply a graded approach to packaging whereby the package integrity is a function of the hazard associated with the radioactive contents. The more hazardous the material, the more robust the packaging. The robustness of the packaging is measured in the ability to withstand various conditions of transport. The three conditions of transport are:
- Routine conditions of transport (RCT) (incident free)
 - Normal conditions of transport (NCT) (minor mishaps)
 - Accident conditions of transport (ACT)
- 3.3 Guidance to SSR-6 can be found in the IAEA safety guide document, SSG-26 'Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material' [5]. This can be considered as relevant good practice (RGP).
- 3.4 Compliance with alternative standards may be allowable under SSR-6; for example, the International Convention for Safe Containers (CSC) [6] for freight containers or the

International Organization for Standardization (ISO) standard for the packaging of uranium hexafluoride (UF₆) for transport [7].

- 3.5 The following guidance highlights the relevant paragraphs in the regulations that refer to these criteria; however inspectors should refer to the exact wording in the regulatory texts and guidance when necessary. The key criticality safety related paragraphs are presented in SSR-6 paras 673 to 686. The definitions for the key terms used in the IAEA Regulations are presented in Section II of SSR-6. The test procedures for normal and accident conditions of transport are presented in Section VII of SSR-6.

Assessment of an Individual Package in Isolation

- 3.6 As described in SSR-6 para. 680 for the single package assessment, it shall be assumed that water can leak into or out of all void spaces of the package, including those within the containment system, irrespective of the outcome of the water immersion / leakage tests, unless the design incorporates special features that would prevent this.
- 3.7 Special features could include multiple independent high standard water barriers, not less than two of which would each remain watertight if the package was subjected to the accident condition tests specified in SSR-6 para. 685(b). However, water ingress / egress over individual barriers still needs to be considered; for example, water shall be assumed to pass from outside the package across the outer barrier or any moisture that may normally be present within the outer barrier shall be assumed to pass across the second (inner) barrier.
- 3.8 The package shall be subcritical following routine conditions (incident free), normal conditions (minor mishaps) (SSR-6 para. 684(b)) and accident conditions of transport (SSR-6 para. 685(b)).
- 3.9 Para. 681 of SSR-6 states that the confinement system shall be reflected by at least 20cm of water unless greater reflection is provided by the surrounding material of the packaging. Where the confinement system remains within the packaging following the accident condition tests prescribed in para. 685(b) of SSR-6, close reflection of the package by at least 20cm of water shall be assumed.

Assessment of Package Arrays under Normal Conditions of Transport

- 3.10 Unlike routine conditions of transport (RCT) (incident free), normal conditions of transport (NCT) represents minor accidents or mishandling of the package that could occur during transit. NCT conditions must be demonstrated for industrial packages (IP-2, IP-3), Type A, Type B and Type C packages.
- 3.11 The package shall be subjected to the normal condition tests specified in SSR-6 para. 684(b).
- 3.12 As stated in SSR-6 para. 684, a number N shall be derived such that 5N packages shall be subcritical. All geometric configurations / arrangements consistent with normal condition tests should be considered such that if they existed in an array of 5N packages then this array would be subcritical; the array geometry itself is chosen which produces the most reactive arrangement. The purpose of the array is to enable the criticality safety index (CSI) to be determined.
- 3.13 The package array shall be reflected on all sides by at least 20cm of water.

Assessment of Package Arrays under Accident Conditions of Transport

- 3.14 Accident conditions of transport (ACT) represent the conditions under which the package sustains damage that is equivalent to that from a severe and credible accident.
- 3.15 The criticality safety assessment should consider the state of the package following the normal condition and applicable accident condition tests specified in paras 684(b) and 685(b) of SSR-6 respectively.
- 3.16 As stated in SSR-6 para. 685, a number N shall be derived such that 2N packages shall be subcritical. The packages in the array shall be orientated so as to maximise the reactivity of the system. This may involve inverting alternate packages so that factors such as neutron interaction and overall fissile densities are maximised. This can be relatively easy to demonstrate for packages with simple cuboid geometries, where the packages will readily 'tessellate' in three dimensions but can be harder to achieve with cylindrical or barrel shaped packages. Reasoned argument may be used to justify why the chosen array shape is bounding.
- 3.17 The bounding parameters determined for the package geometry and material compositions following the mechanical and thermal accident condition tests should be optimised to maximise reactivity. The need to consider package flooding is dependent upon the outcome of the water immersion test (paras 729, 730 of SSR-6) or the water leakage test (paras 731-733 of SSR-6).
- 3.18 The package array shall be reflected on all sides by at least 20cm of water.
- 3.19 Where fissile material escapes the containment system following the tests specified in para. 685(b) of SSR-6, it shall be assumed to escape each package in the array and accumulate in the configuration and moderation that results in the maximum neutron multiplication with close fitting water reflection of at least 20cm.

Assessment of Packages Transported by Air

- 3.20 The requirements for fissile packages transported by air only apply to the assessment of the individual package in isolation.
- 3.21 Para. 683(a) of SSR-6 states that the individual package shall be subcritical under conditions consistent with the Type C package tests specified in SSR-6 para. 734, reflected by at least 20cm of water but with no water in-leakage. Where the Type C package tests have not been carried out, it is indicated in para. 683.2 of SSG-26 that the worst case rearrangement of the package materials should be considered (but with no additional source of moderation included).
- 3.22 Para. 683(b) of SSR-6 indicates that the accident condition tests specified in SSR-6 para. 685(b) for the individual package should also be considered. It shall be assumed that water can leak into or out of all void spaces of the packages unless it can be demonstrated, for example, that not less than two multiple independent high standard water barriers would remain watertight if the package were subjected to the Type C package tests as well as the water in-leakage test as specified in paras 734 and 733 of SSR-6 respectively.

Criticality Safety Index

- 3.23 The criticality safety index (CSI) is a number assigned to a package containing fissile material and is used to provide control over the accumulation of packages.
- 3.24 As stated in SSR-6 para. 686, the CSI shall be obtained by dividing the number 50 by the smaller of the two values derived for N in paras 3.12 and 3.16 above such that CSI

= 50 / N. As suggested in para. 686.3 of SSG-26, the CSI for a package should be rounded up to the first decimal place (never down). However, if this rounding procedure causes a disadvantage, ONR may allow the dutyholder to take credit for more decimal places.

- 3.25 The sum of package CSIs for various freight containers or conveyances shall not exceed those limits presented in Table 11 of SSR-6. This table indicates that the limit on the sum of package CSIs may be increased if the freight container or conveyance is operated under exclusive use whereby all initial, intermediate, final loading / unloading and shipment is carried out by a single consignor.

Confinement System

- 3.26 Para. 209 of SSR-6 defines the confinement system as the assembly of fissile material and packaging components necessary to preserve criticality safety.
- 3.27 In order to fulfil the requirement of para. 838(n)(ii) of SSR-6, the dutyholder's criticality safety assessment should state all the components of the package that ensure criticality safety.

Fissile Exceptions

- 3.28 SSR-6 paras 222(a) and (b) indicates that natural / depleted uranium that is either unirradiated or has only been irradiated in a thermal reactor is excluded from the definition of fissile material. However, these exceptions may not be appropriate for materials such as corrosion products formed from the surfaces of irradiated natural uranium fuel, as these may contain a greater ratio of plutonium to uranium than central parts of the fuel, as indicated in Section 5.1.1 of [8].
- 3.29 SSR-6 para. 222(c) states that material with fissile nuclides less than 0.25g shall be excluded from the definition of fissile material. Paras 222.5 and 222.6 of SSG-26 indicate that this mass limit is per package.
- 3.30 SSR-6 para. 417 defines the provisions by which fissile material may be excepted from the classification of 'FISSILE'. SSR-6 para. 570 defines the consignment / conveyance mass limits for this material. Only one provision defined in SSR-6 para. 417 is allowed per consignment, unless the normal and accident condition tests specified in SSR-6 para. 606 are met, otherwise the fissile material shall be classified as 'FISSILE'.
- 3.31 SSR-6 paras 674 and 675 define the provisions by which fissile material may be excepted from the assessment requirements (paras 676-686 of SSR-6) but not from the classification of 'FISSILE'. The accumulation of the packages containing fissile material is controlled by the CSI.
- 3.32 The World Nuclear Transport Institute (WNTI) has produced guidance [9] on the fissile exception provisions that were introduced in SSR-6. An ONR TAG on the approval of fissile excepted material is currently in production [10].

Irradiated Nuclear Fuel

- 3.33 As stated in SSR-6, para. 677, the isotopic composition of irradiated nuclear fuel shall be based on either that which provides the maximum neutron multiplication during its irradiation history or a conservative estimate, including a measurement before shipment, to confirm the conservatism of the isotopic composition.

Temperature Requirements

- 3.34 SSR-6 para. 673(a)(vi) states that fissile material shall be transported so as to maintain subcriticality during routine, normal and accident conditions of transport, taking into account temperature changes.
- 3.35 SSR-6 para. 679 states that the package shall be designed for an ambient temperature range of -40°C to $+38^{\circ}\text{C}$, unless the competent authority specifies otherwise in the certificate of approval for the package design. Para. 673.8 of SSG-26 states that temperatures resulting from the thermal tests (paras 728 or 736 of SSR-6) should be considered.

Assessment of Unknown Parameters

- 3.36 As stated in SSR-6, para. 676, where the chemical / physical form, isotopic composition, mass, concentration, moderation ratio, density or geometric configuration is not known, the criticality safety assessment shall be performed assuming that these parameters have the value that gives the maximum neutron multiplication, consistent with the known conditions and parameters of the assessment.
- 3.37 Although any bounding values used should make due allowance for uncertainty, there is no requirement to make further conservative allowances in addition to this.

4. RELEVANT STANDARDS AND GUIDANCE

- 4.1 IAEA Safety Standards for Protecting People and the Environment, Specific Safety Requirements No. SSR-6 “Regulations for the Safe Transport of Radioactive Material”, 2012 Edition [4].
- 4.2 IAEA Safety Standards for Protecting People and the Environment, Specific Safety Guide No. SSG-26 “Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material”, 2012 Edition [5].
- 4.3 IAEA Safety Standards for Protecting People and the Environment, Specific Safety Guide No. SSG-27 “Criticality Safety in the Handling of Fissile Material” [11].
- 4.4 IAEA-TECDOC-1768 “Application of the Revised Provision for Transport of Fissile Material in the IAEA Regulations for the Safe Transport of Radioactive Material”, 2012 Edition [12].
- 4.5 International Maritime Organization (IMO), International Convention for Safe Containers (CSC) 1972, as Amended 1993 [6].
- 4.6 International Organization for Standardization (ISO), Nuclear Energy – Packaging of Uranium Hexafluoride (UF_6) for Transport, ISO 7195:5005(E), ISO, Geneva (2005) [7].
- 4.7 Separate TAGs on the assessment of nuclear licensees' arrangements for Criticality Safety, NS-TAST-GD-041 [13], and the Validation of Computer Codes and Calculation Methods, NS-TAST-GD-042 [14], are available.
- 4.8 For information on the quality of PDSRs in general, see the ONR Guidance for Applications [3] and The Purpose, Scope and Content of Safety Cases TAG, NS-TAST-GD-051 [15].
- 4.9 For information on the competence of PDSR authors see the Training and Assuring Personnel Competence TAG, NS-TAST-GD-027 [16].
- 4.10 For information on the criticality assessment process, see ONR Transport Permissioning Process Guide, TRA-PER-GD-012 [17].

5. RELATIONSHIP TO ENFORCEMENT POLICY

- 5.1 The ONR Enforcement Policy Statement (EPS) [18] stipulates the five key principles of enforcement that can be applied to PDSR assessment. Further guidance is given in ONR Guide TRA-PER-GD-001 [2].
- 5.2 **Targeting** – considers which assessments or other regulatory contacts should take priority according to the nature and extent of risks posed by a dutyholder’s operations. The dutyholder’s management competence is important, because a relatively low hazard package poorly managed can entail greater risk to workers or the public than a package with greater potential for hazard, where proper and adequate risk control measures are in place. There is no requirement to perform a detailed criticality safety assessment of all aspects of a package application and the judgement of the inspector should be used to determine whether a full assessment is required, individual components of a criticality safety assessment should be analysed (and to what extent) or a broad overview of the criticality safety assessment will suffice. This can depend on several factors including regulatory knowledge of the dutyholder or user of the package and also the safety significance of the package.
- 5.3 **Proportionality** - within the constraints dictated by the prescriptive nature of the transport regulations, permissioning is founded in making judgements based on a proportionate sample of evidence to inform the regulatory decision. The inspector is expected to adopt a constructive and enabling approach to permissioning when the legal requirements have been met (or the compliance gap is such that it would be disproportionate not to grant an approval).
- 5.4 **Consistency** – Dutyholders managing similar risks expect a consistent approach from enforcing authorities in the advice tendered; the use of enforcement notices, approvals and so forth; decisions on whether to prosecute; and in the response to incidents. ONR inspectors are faced with many variables including the degree of risk, the attitude and competence of management, any history of incidents or breaches involving the dutyholder, previous enforcement action, and the seriousness of any breach, which includes any potential or actual harm arising from a breach of the law. This TAG should provide a framework for the assessment of PDSR’s so that package design criticality safety assessments adopt a consistent approach.
- 5.5 **Accountability and Transparency** – ONR is accountable for its actions. This guidance document describes clear standards and is published on the ONR website, giving dutyholders sight of PDSR submission expectations in regard to the assessment of transport criticality safety.

6. ADVICE TO INPECTORS

General

- 6.1 ONR inspectors should base the amount of resource spent assessing each PDSR upon factors such as: the complexity of the package and package contents, whether the contents have changed from that previously assessed in the current certificate of approval, the safety margin provided by the package design with the worst case fissile material content, the uncertainty of this safety margin, prior knowledge of the dutyholder’s competence or whether or not an independent assessment has been carried out. A consistent approach should be taken for similar applications. Where a PDSR has previously been assessed by ONR or another competent authority, credit may be taken for this and the sampling may be reduced accordingly.
- 6.2 Inspectors may see a range of assessment methodologies utilised in the criticality safety assessment; from reasoned argument (physical effects) through handbook methods to simple or complex Monte Carlo calculations. The methodology adopted by

the dutyholder should be appropriate to the complexity of the contents and design, the safety margin between the calculated neutron multiplication factor and the criticality safety criterion (see paras 6.18 to 6.25 below), and the associated uncertainty of this margin.

- 6.3 Inspectors should expect dutyholders to submit a complete and robust criticality safety assessment. If an inspector considers that key calculations necessary to demonstrate compliance with the IAEA regulations are missing, they should request further evidence from the dutyholder.
- 6.4 The PDSR, referenced from the application, should contain all the documentation necessary for the criticality safety assessment. It is considered good practice that the inspector first reviews the engineering drawings before the criticality safety assessment in order to understand the key geometrical parameters and material isotopic compositions of the transport package. The inspector should then identify all calculations that they would expect to see in order for criticality safety to be demonstrated. Once this has been done, the dutyholder's criticality safety assessment can be reviewed to ensure that the key parameters have been modelled and bounding calculations have been carried out. The ONR engineering inspector should also confirm that the accident conditions assumed to be the most onerous for criticality safety are substantiated by the appropriate test reports.
- 6.5 All of the safety features of the package design should be specified in the PDSR or its appendices.
- 6.6 The geometry and material compositions of the package should be determined from the engineering drawings referenced within the PDSR. As highlighted in para. 673.7 of SSG-26, the effect on reactivity of tolerances on dimensions and material compositions should be considered.
- 6.7 Where the criticality safety assessment relies upon the isotopic composition, geometry or density of key packaging materials, such as neutron absorbers, moderators or reflectors, there should be evidence to substantiate these assumptions. If not, the key parameters should be included in the certificate of approval, unless already clearly specified in the PDSR or supporting documentation, with a recommendation to the ONR compliance inspector to confirm that there is appropriate evidence to substantiate these claims at a future inspection.
- 6.8 Although the assessment should assume that the package is as per its design (taking into account the tolerances), the lifetime history of the package should also be taken into consideration. For example, the way some packages are used could lead to, for example, steel corrosion resulting in a reduction in thickness over time and an increase in the reactivity of the array due to increased neutronic interaction between adjacent transport packages.
- 6.9 Applications may be received that request the validation of transport package designs approved by an overseas competent authority. The criticality safety assessment methodology presented in this document should also be used for these applications.

Assessment Guidance

- 6.10 This section presents suggested guidance in the form of a list of points that the ONR inspector may look for when considering a dutyholder's criticality safety assessment. Although not exhaustive, a criticality safety assessment checklist is also provided in the Appendix.
- i) Comprehensive and bounding fissile inventory identification.
 - ii) The criticality safety assessment should be robust, providing evidence of how the

bounding / worst case content or packaging configuration is defined and demonstrating subcriticality for all reasonably foreseeable scenarios during routine, normal and accident conditions of transport taking into account the contingencies stated in para. 673 of SSR-6.

- iii) The geometry (including tolerances) of the package should be determined from the engineering drawings referenced from the PDSR. The PDSR or engineering drawings should also clearly identify all the materials of the package to allow key information such as the density or chemical composition to be determined.
- iv) Explanation of, and / or quantification of the effect of, all assumptions or pessimisms. Inspectors should look for a systematic approach to applying any pessimisms or assumptions; it is noted that the effect of one optimistic assumption may not be outweighed by a large number of minor pessimisms. Quantification is generally necessary when uncertainties are large or not well defined by explanation.
- v) The impact of the accident conditions, such as the drop, fire and water immersion / leakage tests, on the package geometry and material composition should have been considered in the criticality safety assessment.
- vi) Alternative modelling or simplifications compared to the actual package drawings should be shown / argued to have either, an insignificant effect on, or lead to a higher neutron multiplication factor.
- vii) The dutyholder should have carried out all calculations that the ONR inspector would expect to see presented in the criticality safety assessment. From this information, it should be possible to confirm / verify that the system has been adequately characterised in terms of optimal reactivity conditions, within the bounding parameters. Any scenarios that could potentially lead to more reactive configurations should be raised with the dutyholder.
- viii) The dutyholder should present evidence that they can comply with any criticality safety related conditions included in the certificate of approval.
- ix) Appropriate choice of calculation methods.
- x) Adequate sampling and convergence of Monte Carlo computer calculations where appropriate.
- xi) Adequate validation and verification of calculation methods.
- xii) Cross-checks of calculations using an independent method / assessor should be carried out where appropriate; for example, for novel applications where ONR has limited previous experience, such as burnup credit, or where anomalous behaviour may occur. Due to the material and geometrical complexity of fissile transport packages, it is likely that this may only be achieved via the use of Monte Carlo computer codes.
- xiii) The dutyholder may employ an independent assessor to carry out the cross-check calculations or ONR can pass the work to a technical support contractor (TSC) working under contract to ONR to perform the appropriate calculations and / or review as appropriate. The ONR criticality safety inspector will guide the TSC in the level and depth of sampling which may be influenced by the safety significance of the submission. The cost of the independent review will be borne by the dutyholder.
- xiv) Confirmation that the dutyholder's criticality safety analyst and independent reviewer are suitably qualified and experienced (SQEP).

Fissile Inventory

- 6.11 Fissile nuclides are defined by para. 222 of SSR-6 as uranium-233, uranium-235, plutonium-239 and plutonium-241.
- 6.12 A criticality safety assessment is required for systems containing these fissile nuclides. Dutyholders should determine the bounding fissile inventory taking into account all fissile nuclides present.
- 6.13 In uranium systems, the dominant isotopes are usually uranium-235, which is fissile, and uranium-238, which is fissionable; transport assessments may also be submitted that consider the fissile nuclide uranium-233. In plutonium systems, the dominant isotopes are usually plutonium-239 and plutonium-241, which are fissile, and plutonium-240, which is fissionable.
- 6.14 As indicated in para. 222.3 of SSG-26, where there are significant quantities of other fissile / fissionable nuclides that have the potential for criticality, for example curium or americium isotopes, the dutyholder should consider carrying out a criticality safety assessment. Advice may be sought from the ONR criticality safety inspector.
- 6.15 It should be noted that some exotic species have relatively low minimum critical masses. Hence, in cases where exotic species are modelled as uranium-235 or plutonium-239, evidence should be provided that the representation is suitably conservative.
- 6.16 ONR expects the dutyholder's criticality safety assessment to identify safe limits and conditions with regard to the isotopic composition. The ONR criticality safety inspector may ask the ONR compliance inspector to confirm, at a future inspection, that there is evidence that the dutyholder can comply with these limits and conditions.
- 6.17 Inspectors may encounter criticality safety assessments for mixed plutonium / uranium systems. These can be isotopically complicated with the assessment relying on assumptions for the ratios of both plutonium and uranium isotopes. Note that the most reactive ratio will vary depending on the amount of moderator in the system and that validation evidence may be more limited than for some other systems [19]. Dutyholders should demonstrate that they have considered these issues.

Criticality Safety Criterion

- 6.18 The IAEA Regulations refer to the need to ensure that packages and arrays of packages are 'subcritical'. This term is open to interpretation and criticality safety criteria are not specified. However, para. VI.38 of SSG-26 indicates that typical practice for transport packages is to use a minimum safety margin of subcriticality of 0.05. This safety margin is used by the USA, Germany, Japan and most other countries around the world. The French CA allows a minimum safety margin of subcriticality of 0.02 for package arrays under both normal and accident conditions of transport.
- 6.19 As a general expectation, any calculated values of effective neutron multiplication factor (k_{eff}) must be appropriately adjusted to cater for the systematic code / data bias and uncertainties, as determined by the validation data. Dutyholders should demonstrate that:

$$K(\text{code}) + \text{bias} + \text{uncertainties} \leq L$$

Where, for example, a subcritical margin of 0.05 gives $L = 0.95$, $K(\text{code})$ is the k_{eff} value from the computer model and the uncertainties include a statistical uncertainty on the Monte Carlo k_{eff} value of typically three standard deviations.

- 6.20 Para. VI.38 of SSG-26 indicates that a value for the subcritical margin lower than 0.05 may be appropriate for certain packages but such values will require justification based on available validation, a demonstrable understanding of the system and the effect of potential changes.
- 6.21 It is noted that in para. AX.5 of an earlier version of the IAEA guidance [20], dating back to 1990, a safety margin of subcriticality of 0.03 was considered acceptable. Based on appropriate justification, the UK CA has previously accepted a safety margin such as this for low enriched uranium oxide systems.
- 6.22 The margin of subcriticality may need to be increased beyond that typically applied where there is a lack of critical experimental data relevant to the assessment or where there is a need to extend beyond the range of applicability. For example, the safety margin of subcriticality may need to be greater than 0.05 where the validation data indicates that the computer code / nuclear data library combination under predicts k_{eff} .
- 6.23 The dutyholder's criticality safety assessment should specify the criterion that they are working to and (provided that this is deemed acceptable via appropriate justification), the ONR inspector should confirm that this criterion is met. For example, the ONR inspector may choose to confirm that the validation experiments chosen to determine the systematic bias in the code and nuclear data are appropriate. The dutyholder cannot exceed their own criticality safety criterion.
- 6.24 Where the criticality safety criterion is challenged, following review by the ONR inspector, the dutyholder may first consider reducing the pessimisms, where possible, in the various assumptions made within the criticality safety assessment.
- 6.25 ONR recognises that overall safety (covering criticality, radiological and conventional safety) as well as security, may on occasion be best served by allowing a smaller margin of subcriticality than usually implemented. This may include highly unlikely scenarios beyond the explicit regulatory requirements of SSR-6, with the frequency of occurrence of $<10^{-7}$ per annum, as indicated in para. 631 of the ONR SAPs [1]. However, the dutyholder would need to remain mindful of the advice provided above and clearly demonstrate the overall safety benefits with a full and rigorous justification of their approach. Based on guidance provided by the US Nuclear Regulatory Commission (NRC) [21], utilised for US site nuclear criticality safety, it is unlikely that ONR would accept a safety margin of subcriticality of less than 0.02. The dutyholder should engage early with ONR to discuss their arguments and to ensure there are no other ways of achieving the same aim. It is noted that any holistic safety arguments accepted by the ONR may not be recognised by overseas competent authorities for international transport of the package.

Criticality Safety Control

- 6.26 In addition to the use of geometrical constraints and isotopic composition, there are several other parameters, control of which can be used to achieve criticality safety:
- i) **Fissile Mass.** Criticality safety can be achieved by controlling the mass of fissile material within the transport package.
 - ii) **Moderation.** The critical mass of fissile material can be significantly reduced by the presence of moderating material. All moderating material that may reasonably be present within the transport package should be considered and the criticality safety assessment shall demonstrate that safety is maintained under bounding conditions; this may lead to differing conditions considered for the single package, normal and accident condition array. Common sources of moderation are hydrogenous materials such as water, oil or polyethylene. It should be noted that dutyholders may base their criticality safety assessment on limited moderation arguments. Here, it is argued that

while some moderator may be present, there will be an insufficient quantity for the system to exceed the applicable criticality safety criterion. For the individual package in isolation, the use of multiple high standard water barriers may prevent water from entering certain parts of the package. Under these conditions, lower reactivities are expected for thermal and intermediate neutron systems. Such arguments may be acceptable if adequately substantiated.

iii) **Concentration.** The reactivity of fissile material in solution or suspension will vary as a function of the concentration of the fissile material. This is largely due to the competing effects of dilution of the fissile material (reducing density), moderation and absorption by the liquid. There will be a concentration at which the reactivity is highest, known as the optimum concentration. The criticality safety assessment shall demonstrate that safety is maintained even at optimum concentration, unless evidence can be provided that this concentration cannot be achieved under both normal and accident conditions of transport. The optimum concentration for a single package in isolation may not be the same as for an array.

iv) **Density.** For fissile material in monolithic solid form, there will generally be a range of possible densities, up to the maximum theoretical density. It is well established for this material that the critical mass decreases with increasing density [22]. Hence, criticality safety assessments should generally consider the maximum theoretical density unless evidence can be provided that this density cannot arise under both normal and accident conditions of transport. Care is required for packages in an array, or those with multiple fissile regions, to ensure that greater neutron interaction does not occur for higher volume / lower density fissile material.

v) **Interaction.** For both normal and accident conditions of transport, arrays of packages shall be considered. Maximum reactivity is normally achieved when the packages are close packed, with the external surface area of the array minimised, in order to maximise the transfer of neutrons to adjacent packages and to minimise the leakage from the external boundary of the array. However, for some fast or intermediate systems, a gap between the packages filled with a water spray (to simulate firefighting) may be more reactive; see paras VI.48 to VI.58 of SSG-26 for further information. Consideration should be given to changes in the package geometry as a result of the prescribed normal and accident condition tests.

vi) **Reflection.** The reactivity of a fissile system can be increased by the presence of reflecting material. A close-fitting water reflector of at least 20cm shall be assumed to surround both the single package and array transport models as required by paras 681, 683(a), 684(a) and 685(a) of SSR-6.

vii) **Heterogeneity Effects.** Heterogeneous systems may result in higher reactivities than the equivalent homogeneous systems. This can occur for uranium, plutonium and mixed systems over a range of enrichments and isotopic compositions. Care should be taken to ensure that the most reactive homogeneous or heterogeneous system has been identified for the particular moderation state considered. The impact of neutron absorbers should be taken into account and any claim for homogeneity should be substantiated, as heterogeneity effects can also be observed for absorbers [23]. For uranium systems enriched up to ~10wt% U-235/U, [24] indicates that heterogeneous critical masses are smaller than the corresponding homogeneous values; although there are anomalies to this. Figure 11 of [25] indicates that for mixtures of uranium in water at any enrichment, the heterogeneous minimum critical volumes are always smaller than their homogeneous equivalents. Para. 417.3 of SSG-26 indicates that heterogeneous effects have been observed for fissile material enriched up to 1wt% U-235/U, in certain mixtures for particle sizes greater than 127µm (0.005"); however, the agglomeration of smaller particles than this into larger agglomerate sizes could also lead to heterogeneous effects. Fissile material in the form of pellets is typically designed for use in a heterogeneous arrangement.

viii) **Neutron Absorbers.** Neutron absorbers are often used in transport packages to preserve criticality safety. The ONR compliance inspector should be asked to confirm that there is evidence that the isotopic composition and density of any neutron absorber material assumed in the criticality safety assessment is present in the actual package. The ONR engineering inspector should also be asked to confirm that following the regulatory normal and accident condition tests, the mass and location of neutron absorber in the transport package remains as assessed.

Free Drop, Stacking, Penetration and Mechanical Tests

- 6.27 The IAEA Regulations, paras 722 to 724 and 727 of SSR-6, require the package to undergo various mechanical tests (free drop, stacking and penetration) under both normal / accident conditions of transport.
- 6.28 The inspector should make use of the discipline knowledge within the ONR team working on the same package design. The ONR engineering and compliance inspectors should be asked to confirm the key assumptions, as appropriate, that have been made in the criticality safety assessment. For example, the ONR engineering inspector should confirm that the correct mechanical testing was carried out for maximum damage and provide an analysis of the impact of that damage. This will allow the key assumptions made in the dutyholder's criticality safety assessment to be confirmed.
- 6.29 However, the ONR criticality safety inspector should not assume that the other discipline assessors understand the worst case considerations necessary for the criticality safety assessment.
- 6.30 For transport packages carrying fuel assemblies, accident conditions of transport may lead to a number of effects such as fuel breakup (resulting in the formation of sludge and missing pins), fuel pin / absorber plate displacement, flux trap collapse or fuel assembly 'bird caging'. Guidance should be sought from the ONR engineering inspector regarding the appropriate combination of effects that should be considered.
- 6.31 Compliance with the normal and accident condition regulatory requirements may be demonstrated by for example, providing evidence of physical testing, calculation (such as finite element analysis) or reasoned argument (see para. 701 of SSR-6).
- 6.32 In order to demonstrate regulatory compliance, the impact of all the relevant normal and accident condition tests and the rationale for the testing parameters (whether tested, or not) should be clearly set out, or referred to in the criticality safety assessment. For example, drop orientations and internal packing arrangements which cause the maximum damage should be explained and the potential for slumping of materials (such as lead in the drop or fire test), loss of containment and quantification of the material lost should all be considered, alongside any other potential for damage from physical impact or heat.
- 6.33 Although assuming that the contents of a package defy gravity is bounding, it is acceptable for the dutyholder to justify less onerous approaches. However, there are scenarios where the assumption that items fall naturally under gravity may not hold. For example, where components may become physically lodged towards the end of a package; if the package could topple over following the normal or accident condition tests with the fissile material near the lid (or base) of one package becoming adjacent to the fissile material near the lid (or base) of another package; or fissile powder could become lodged in non-fissile components or adhere to parts of the package when wet.

Thermal Test

- 6.34 Para. 728 of SSR-6 states that the thermal test shall fully engulf the specimen for 30 minutes at an average temperature of at least 800°C. This could potentially lead to charring of the outer materials, for example the thermal shield of the package, with the loss of key nuclides (such as hydrogen) as well as the melting and reconfiguration of internal materials such as polyethylene. This could result in the reduction in effectiveness of the neutron absorber within the package if the associated moderator is lost.
- 6.35 Although hydrogen nuclei moderate neutrons, they also act as an absorber so their removal could lead to an increase in system reactivity via enhanced interaction between adjacent packages with the remaining charred material acting as a moderator.
- 6.36 If, following the thermal test, it is possible for the fissile material to oxidise and breakup, any unfavourable geometry / sludge configuration that could potentially occur, should be considered.
- 6.37 The dutyholder shall demonstrate that the post-thermal test package material compositions assumed in their criticality safety assessment are bounding, in accordance with para. 3.36 above.

Water Spray and Immersion Tests

- 6.38 Paras 721, 729 and 730 of SSR-6, detail the requirements for the water spray and immersion tests. Any claim that the dutyholder makes for the absence of leakage into the package under either normal or accident conditions of transport should be substantiated by the ONR engineering inspector and can only be made if there are special features such as multiple barriers, SSR-6 para. 680(a), in the case of the assessment of an individual package in isolation.
- 6.39 For package arrays under normal conditions of transport, para. 684(a) of SSR-6 states that there shall not be anything between the packages and that the package arrangement shall be reflected on all sides by at least 20cm of water.
- 6.40 For package arrays under accident conditions of transport, para. 685(a) of SSR-6 requires optimal hydrogenous moderation between the packages with the package arrangement reflected on all sides by at least 20cm of water.

Differential Flooding

- 6.41 Differential flooding within the package can increase neutron interaction between fissile material in adjacent packages or between fissile regions in the same package. This could occur due to the particular geometry of the transport package or following ice formation at low temperatures that could block drainage flow paths. The ONR engineering inspector should be able to advise on where this is possible in the package following either normal or accident conditions of transport.
- 6.42 If credit is taken for space fillers occupying void space within the package, the ONR engineering inspector will need to confirm that appropriate evidence has been provided within the PDSR to demonstrate that following the regulatory normal and accident conditions of transport tests, water will be excluded from these regions.

Irradiated Nuclear Fuel

- 6.43 Taking credit for the irradiation of the nuclear fuel, known as 'burnup credit', involves suitable inventory / reactivity prediction calculations as well as verification of the isotopic composition.

- 6.44 *Inventory Prediction.* The isotopic composition produced from the inventory prediction calculation shall provide a conservative estimate of the neutron multiplication for the package assessment, taking into account, as appropriate, the initial fissile content, power history, boron concentration, burnable neutron absorbers, irradiation and cooling time for example. Post irradiation examination (PIE) of appropriate irradiated nuclear fuel may be used to validate the inventory prediction calculation.
- 6.45 *Reactivity Prediction.* For the reactivity prediction calculations, appropriate actinide and fission product nuclides should be chosen depending on the type of burnup claimed; actinide only or actinide plus fission products for example. The axial / radial burnup profile should also be appropriately represented.
- 6.46 *Verification of Isotopic Composition.* The conservatism of the isotopic composition assumed shall be confirmed via measurement. This could be via PIE or monitoring.
- 6.47 Further guidance on the consideration of irradiated nuclear fuel is given in [8, 26, 27, 28 and 29].

Temperature

- 6.48 Historically, criticality safety assessments have used nuclear data at room temperature (approximately 20°C). However, a change in temperature could lead to an increase in reactivity; the magnitude of which is dependent on the package design.
- 6.49 An increase in reactivity could occur at higher temperatures due to Doppler 'broadening' of fission, absorption and scattering cross-sections. Changes in the balance between these processes could occur in systems for which resonance region neutron interactions are significant. Also where plutonium is present in a well moderated system, the higher energies of thermalized neutrons could increase fissions in the lowest energy plutonium-239 resonance.
- 6.50 An increase in reactivity as the temperature drops could occur due to thermal contraction of the moderating material (increased moderator density leads to enhanced thermalisation and reduced neutron leakage), Doppler 'narrowing' of non-fissile nuclide absorption resonance cross-sections or effects due to the reduced energy of thermalized neutrons. This could occur for low enriched systems, for example.
- 6.51 Due to the geometrical complexity of transport packages and the variety of materials used in the design, it is considered difficult to know for sure which effect will dominate. In order to explicitly determine the impact of temperature on criticality safety it is likely that temperature dependent calculations may need to be carried out. However, this may be mitigated by an understanding of how temperature affects the system and the size of the margin to the criticality safety criterion. In order to understand the reason for the impact of temperature on the k_{eff} of the transport package, it is considered good practice for the output file to be examined.
- 6.52 Most nuclear codes and data libraries currently used around the world cannot explicitly carry out temperature dependent calculations below approximately 20°C. However, if the higher temperature calculations indicate that k_{eff} decreases with temperature, a suitable extrapolation methodology may be employed to provide an estimate of the potential impact on k_{eff} at lower temperatures.
- 6.53 An appropriate nuclear data library and collision processor, such as JEFF BINGO or equivalent, should be used in the evaluation of the impact of temperature on the criticality safety of the transport package.
- 6.54 Temperature changes will also have an impact on the density of the package materials. Bounding assumptions should be made for the key materials of the package, for example the moderator, in accordance with para. 3.36 above. The low

thermal coefficients of expansion for some packaging materials may not lead to a significant impact on criticality safety for the range of temperatures considered.

- 6.55 Freezing and the formation of ice could, for certain package types, result in the deformation of, for example, fuel elements, leading to possible breakup and a more reactive arrangement. Temporary freezing of part of a package could be significant so if this contingency has not been considered in the criticality safety assessment, the ONR engineering inspector will need to confirm that evidence has been provided in the PDSR to demonstrate that it cannot occur.
- 6.56 If a dutyholder is unable to carry out temperature dependent criticality calculations and it is considered possible that the criticality safety criterion could be challenged, a TSC can be employed to confirm that criticality safety will be maintained following any appropriate change in temperature. The cost of the assessment work carried out will be borne by the dutyholder.
- 6.57 Where the criticality safety criterion is challenged by the temperature dependent criticality calculations, the dutyholder may explore the sensitivity to other assumptions made within the safety case in order to demonstrate that the impact of temperature is outweighed by other effects. Such an approach would require appropriate substantiation.
- 6.58 An ONR position statement regarding the consideration of temperature on nuclear criticality safety in transport applications is presented in [30]. An agreed UK industry position [31] has also been produced by the Transport Container Standardisation Committee (TCSC).

Calculation Methods

- 6.59 As highlighted in para. 6.2 above, ONR inspectors may see a range of assessment methodologies utilised in the criticality safety assessment; from reasoned argument through handbook methods to simple or complex Monte Carlo calculations.
- 6.60 Some applications may contain the results of multi-parameter criticality surveys, involving many hundreds or even thousands of Monte Carlo simulations to investigate combinations of parameters. Typically the surveys require the use of automated procedures to generate the input data for the calculations.
- 6.61 The dutyholder may argue that analysing the effect of perturbation of each individual parameter in detail is not required where the presence of other demonstrable conservative assumptions can be shown (or reasoned) to outweigh any effect and / or it is clear that any effect on k_{eff} would not challenge the criticality safety criterion.
- 6.62 It is noted that assessments based on inadequate surveys, where there is a lack of a systematic approach, or preconceived assumptions, may lead to a failure in finding the maximum possible k_{eff} . Inspectors may wish to inspect the dutyholder's arrangements for ensuring the quality of the calculations and management of results.
- 6.63 The ONR inspector may seek evidence from the dutyholder that their Monte Carlo calculations are adequately sampled and converged.
- 6.64 The calculation methods and data used in criticality safety assessments should be verified and validated for the expected range of conditions.
- 6.65 Validation should be against experiment whenever this is reasonably practicable. Note that there is a large amount of validation data available in the ICSBEP (International Criticality Safety Benchmark Evaluation Project) database. Where suitable experimental data is not available, validation by comparison with an independent method may be acceptable. Further guidance on validation is given in [14].

- 6.66 Where criticality safety is reliant upon unusual materials (such as neutron absorbers), where the criticality models have complicated neutron spectra (multiple energy peaks) or where the calculated neutron multiplication factors lie close to the criticality safety criterion, ONR may require a rigorous justification of the experimental bias. This may be based upon statistical modelling and sensitivity profiling [32].
- 6.67 Verification should demonstrate that the calculation method or computer code has been used correctly, in accordance with its specification, and for situations for which it has been validated.

Peer Review

- 6.68 The purpose of the internal peer review of the ONR criticality safety inspector's assessment report is to ensure that the conclusions of the report are soundly based, consistent and proportionate. The peer review shall also confirm that the ONR inspector's assessment report provides sufficient evidence that the application has been adequately assessed and that all relevant IAEA regulatory requirements [4] have been satisfactorily addressed. It shall also ensure that there is a consistent approach across all ONR criticality safety inspectors.
- 6.69 The peer review should confirm that all criticality related parameters (for example either fissile or non-fissile mass limits) in the draft certificate of approval (UK designs) or draft validation certificate (overseas approved designs) are consistent with the values assumed in the criticality analysis. If a limit in the certificate appears more restrictive than that assumed in the criticality analysis, this should be discussed with the ONR criticality safety inspector as although 'safer', there could be compliance implications for the dutyholder. Further information on the peer review process can be obtained from [17].
- 6.70 ONR Guide NS-TAST-GD-084 [33] defines those reports for which peer review is mandatory prior to issue ('Major Reports') and those reports for which peer review is not necessarily mandatory ('Routine' and 'Other' reports).
- 6.71 In accordance with ONR Guide NS-TAST-GD-085 [34], the relevant Delivery Lead is responsible for deciding whether a peer review is required. Any decision taken not to conduct a peer review on a 'Routine Report' should be documented, with the reasons given in ONR's documentation and records management system (TRIM).

Quality Assurance

- 6.72 Changes to the package design over time should be managed and recorded. These should be clearly catalogued in the PDSR or package design safety review report and / or within the dutyholder's management system. All changes since the previous application should also be described in full.
- 6.73 Inspectors should check that all the sections of the PDSR are linked and referenced and that other references are clearly listed and are current. The engineering drawings used for key parameters of the criticality safety assessment should be referenced, either directly or via drawing lists in the PDSR.
- 6.74 Inspectors may seek maintenance or inspection records that relate to the criticality safety of the package. This might be done, for example, to seek assurance that certain design features have not changed over time due to, for example, material degradation or wear and tear.
- 6.75 Inspectors should assess whether an appropriate methodology has been selected to demonstrate the criticality safety of the package.

- 6.76 The criticality safety assessment should have been adequately verified and validated (in particular any computer codes). If a limit on the validity of an approach exists, evidence should be provided to show that the approach is used within the valid region or the use of inferred / extrapolated information is substantiated.
- 6.77 The criticality safety assessment should have been reviewed by another competent person to the author.

Certificate of Approval

- 6.78 A detailed description of the fissile material content should be included in the transport certificate of approval as well as the information required by para. 838 of SSR-6. Additional key parameters or assumptions, upon which the criticality safety assessment is reliant, should also be included as appropriate. For example, where moisture or polyethylene / oil is present within the package, it may be necessary to include a maximum moderator mass or hydrogen density limit (taking into account increases in material density that can occur as the temperature is lowered). Temperature restrictions may also be included in the certificate of approval.
- 6.79 Where additional assessment work has been carried out by the dutyholder in order to justify the criticality safety of their transport package and the PDSR has not been updated with its inclusion, the additional work should be referenced in the certificate of approval.
- 6.80 Unless justified as acceptable by the criticality safety assessment, the certificate should include the wording 'beryllium, graphite and substances enriched in deuterium shall not be carried'. However, suitable wording may be included to take into account the presence of any trace quantities considered acceptable.
- 6.81 The length of validity for certificates of approval is up to five years, at the discretion of ONR. For the validation of overseas approved designs, the expiry date should align with that of the base certificate of approval.

Certificate Renewal

- 6.82 In accordance with para. 4.2 of the ONR Guidance for Applications [3], a periodic design review report should accompany the PDSR for certificate renewals.
- 6.83 In regard to the criticality safety assessment, the dutyholder should review their calculations and demonstrate that any new computer code version or nuclear data library update will not alter the conclusions presented.

7. REFERENCES

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8. ABBREVIATIONS

ACT	Accident Conditions of Transport
CA	Competent Authority
CSC	International Convention for Safe Containers
CSI	Criticality Safety Index
EPS	Enforcement Policy Statement
IAEA	International Atomic Energy Agency
ICSBEP	International Criticality Safety Benchmark Evaluation Project
IMO	International Maritime Organization
INF	Irradiated Nuclear Fuel
IP	Industrial Packages
ISO	International Organization for Standardization
JEFF	Joint Evaluated Fission and Fusion File
k_{eff}	Effective Neutron Multiplication Factor
MOX	Mixed Plutonium / Uranium Oxide
NCT	Normal Conditions of Transport
NRC	Nuclear Regulatory Commission
ONR	Office for Nuclear Regulation
PDSR	Package Design Safety Report
PIE	Post Irradiation Examination
RCT	Routine Conditions of Transport
RGP	Relevant Good Practice
SAPs	Safety Assessment Principles
SQEP	Suitably Qualified and Experienced Person
SSG	Specific Safety Guide
SSR	Specific Safety Requirements
TAG	Technical Assessment Guide
TCSC	Transport Container Standardisation Committee
TSC	Technical Support Contractor
UF ₆	Uranium Hexafluoride
WNTI	World Nuclear Transport Institute

9. APPENDIX: CRITICALITY SAFETY ASSESSMENT CHECKLIST

#	Question	SSR-6 para.
1	For irradiated nuclear fuel (INF) has the irradiation giving the highest reactivity been assumed?	677(a)
2	Will the package retain a minimum dimension of 10 cm and prevent the entry of a 10 cm cube following the tests specified in para. 678?	678
3	Does the package design meet the requirements of either para. 680(a) or 680(b)? If yes, go to 5.	680 682
4	Is a single package subcritical under all the conditions specified in para. 682 if flooded to the worse possible extent and reflected by 20 cm of water?	680
5	Identify the confinement system as defined in para. 209.	681
6	Does the confinement system remain within the package following the tests specified in para. 685(b)? If yes, go to 8.	681
7	Is the confinement system subcritical under all the conditions specified in para. 682 if flooded to the worse possible extent and reflected by 20 cm of water.	681 682
8	Is air transport required? If no, go to 10.	683
9	Is a single package subcritical if reflected by 20 cm water and subject to the tests in para. 683(a) ¹ but without water in-leakage?	683
10	Has a number N been derived such that 5N packages under the conditions defined in para. 684(a)-(b) are subcritical?	684
11	Is the condition of the package assumed in the criticality assessment consistent with the results of the tests specified in para. 684(b)? Would different tests produce packages giving a higher reactivity? Confirmation from the ONR engineering inspector required.	684(b)
12	Has the geometry and moderation of the fissile material been demonstrated to give the highest reactivity consistent with the results of the tests specified in para. 684(b)?	676
13	Has a number N been derived such that 2N packages under the conditions defined in para. 685(a)-(b) are subcritical?	685
14	Is the condition of the packages modelled in the criticality assessment consistent with the results of the tests specified in para. 685(b)? Would different tests produce packages giving a higher reactivity? Confirmation from the ONR engineering inspector required.	685(b)
15	Has the geometry and moderation of the fissile material been demonstrated to give the highest reactivity consistent with the known fuel data and the results of the tests specified in para. 685(b)?	676
16	Does any part of the fissile material escape from the containment system following the test specified in para. 685(b)? If no, go to 18.	685(c)
17	Has the fissile material escaped from the containment been configured in its most reactive condition?	685(c)
18	What is the CSI?	686

¹ Unless this is an application for a Type C package design, these tests will not have been carried out and complete destruction of the package should have been assumed. Consideration of water ingress is not required but the effect of moderating materials present in or as part of the package must be assessed.