



ONR GUIDE			
Shielding and Dose Rate Safety Assessment of Transport Packages			
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1. INTRODUCTION

1.1 The ONR (Office for Nuclear Regulation) has prepared a suite of Technical Assessment Guides (TAGs) 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, 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 technical assessment guide is one of these guides.

2. PURPOSE AND SCOPE

2.1 This TAG provides guidance to ONR Transport Inspectors for assessing the adequacy of shielding designs and tests carried out on packages, as described in Package Design Safety Reports (PDSRs) submitted in support of requests for design approvals. The term 'design approvals' is used in this document to represent any type of transport permissioning activity including, for example; new package designs, modifications, content changes, shipment approvals etc.

2.2 The TAG is limited to the aspects of the transport regulations that specify the dose rates around packages. The guidance does not extend to the other safety attributes of transport packages designs, namely those of; containment, prevention of criticality and prevention of damage caused by heat. The TAG does not apply to the assessment of special form capsule designs, which have no dose-limiting design requirements in the regulations.

2.3 Transport regulation does not end after a certificate of approval has been issued. Whilst this document is aimed towards assisting shielding specialists undertaking the assessment of the PDSR, consideration is also given to operational use of the package. This may be in the form of restrictions imposed on the certificate that ONR may choose to consider in future inspections.

2.4 This guidance should be applied to applications for:

- new package designs
- modifications to package designs
- certificate renewals
- extensions

of Type B, Type C, Uranium Hexafluoride (containing >0.1kg of Uranium) and fissile packages (not excepted under the relevant fissile exceptions).

2.5 Excepted packages, Industrial Packages (IP's) and Type A Packages that do not carry fissile materials, along with Uranium Hexafluoride Packages carrying less than 0.1 kg of uranium, do not require Competent Authority (CA) approval. Such packages are self-approved and certified by the appropriate duty holder. However, this guidance may still be used by ONR inspectors if there is a requirement to inspect self-approved packages, for compliance assurance purposes. Packages that are self-approved should have safety documentation that adopts the same graded approach discussed in this TAG.

2.6 This Transport TAG contains guidance to advise and inform ONR staff in the exercise of their regulatory judgment.

- 2.7 As with all guidance, inspectors should use their judgement and discretion in the depth and scope to which they employ this guidance.

3. LEGISLATION GOVERNING THE TRANSPORT OF RADIOACTIVE MATERIALS

- 3.1 The opening sections of the '*Transport Permissioning Assessment*' guidance document *TRA-PER-GD-001*, and the '*Guidance for Applicants*' for UK Competent Authority Approval' *TRA-PER-GD-014* (known as the *Applicants Guide*) summarise the legislative framework governing the transport of radioactive materials and ONR's role as a UK Competent Authority. This framework is closely based on the IAEA safety requirements document, *SSR-6 'Regulations for the Safe Transport of Radioactive Material'* [1]. Consequently, the requirements in SSR-6, although not legally binding themselves, provide the standards against which transport safety cases may be assessed. Clearly any formal communications with duty holders or enforcement action being considered by ONR inspectors or permissioning documents should make reference to the appropriate UK legal provisions for the mode of transport in question. ONR should also notify the other GB Competent Authorities as necessary and as defined in the appropriate Agency Agreement or MoU.

IAEA Regulations

- 3.2 The IAEA Regulations apply a graded approach to packaging whereby the package integrity is proportionate to the hazard associated with the radioactive contents. The more hazardous the material, the more robust the packaging. Packaging robustness is measured in the ability to withstand various conditions of transport. The three conditions of transport are:

- Routine Conditions of Transport (RCT), no incidents;
- Normal Conditions of Transport (NCT), minor mishaps;
- Accident Conditions of Transport (ACT), credible accidents.

- 3.3 The following guidance highlights the relevant paragraphs in the regulations that refer to these conditions, however inspectors should refer to the exact wording in the regulation texts and guidance when necessary. A summary of relevant paragraphs of SSR-6 considered during the assessment is tabulated in Appendix 1.

Routine Conditions of Transport

- 3.4 Under Routine conditions of transport, the assessment should assume that the package is as per the design.
- 3.5 SSR-6 states that: *A package shall be so designed that it provides sufficient shielding to ensure that, under routine conditions of transport and with the maximum radioactive contents that the package is designed to contain, the radiation level at any point on the external surface of the package would not exceed the values specified...* [SSR-6 para. 617].
- 3.6 The introduction of this paragraph in the 2012 edition of the regulations was implemented by IAEA members to ensure that packages are correctly *designed* to carry the maximum contents without exceeding regulatory limits, so that radiation safety no longer solely relied upon consignors' pre-shipment survey measurements (which are still a regulatory requirement).
- 3.7 Dose rates on the package surface should be demonstrated to be below maximum dose rate levels within the PDSR. The maximum dose rate levels in the regulations

are; 5 $\mu\text{Sv/h}$ for excepted packages [SSR-6 para. 516]; 2 mSv/h for IP, Type A, Type B and Type C packages [SSR-6 para. 527]; and 10 mSv/h for packages carried under exclusive use conditions [SSR-6 para. 528].

- 3.8 Paragraph 617 also requires that dose rates around the vehicle or conveyance to be *taken into consideration* in the design [SSR-6 paras. 566b, 573]. Inspectors *may wish to check* whether dose rates around the vehicle/conveyance may be challenged, for example if it is known how many, and in which configuration packages are expected to be transported. When addressing the vehicle/conveyance dose rates, the exact values may not be known during the package design phase, but the idea is to question whether the package can be transported in its intended manner (e.g. multiple packages in an unshielded vehicle may exceed the vehicle/conveyance dose rate limits).
- 3.9 Dose rates must not exceed 2 mSv/h at any point on the surface and 0.1 mSv/h at 2 metres from the vehicle/conveyance [SSR-6 para. 566]. The PDSR should *account for* the expected dose rates on the underside, the top, the sides, the front and the back of the vehicle or conveyance.
- 3.10 For applications relating to packages being transported under exclusive use, dose rates must not exceed 2 mSv/h on the external surface of the vehicle including the upper and lower surfaces [SSR-6 para. 573].
- 3.11 For exclusive use applications for transportation by open vehicle, dose rates must not exceed 2 mSv/h on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load and on the lower external surface of the vehicle. In addition, dose rates must not exceed 0.1 mSv/h at any point at 2 m from the vertical planes represented by the outer lateral surface of the vehicle [SSR-6 para. 573].
- 3.12 If only one package is to be transported in a conveyance, this fact can be simply stated in the PDSR and no account needs to be made for vehicle/conveyance dose rate limits (as they are bounded by the package dose rate limits).
- 3.13 There are other package and material dose rate requirements stipulated in SSR-6, but these are not applicable to Competent Authority package design approvals (e.g. transport index).

Normal Conditions of Transport

- 3.14 Normal Conditions of Transport encompass minor accidents or mishandling of the package that is likely to occur during transit [SSR-6 paras. 719-725]. Compliance with NCT conditions must be demonstrated for IP-2, IP-3, Type A, Type B and Type C packages.
- 3.15 The PDSR should demonstrate that there is not more than a 20% increase in dose rate on the package surface following NCT tests.
- 3.16 There are subtle differences in NCT test requirements for different package types (a graded approach is adopted and test requirements are less severe for type IP packages) and alternative requirements for packages that have already been tested against other requirements [SSR-6 paras. 624, 626-630, 648]. Type B(U), B(M) and C packages [SSR-6 paras. 652, 667 and 669] refer back to the Type A [SSR-6 para. 648] requirement.

Accident Conditions of Transport

- 3.17 Accident Conditions of Transport encompass the conditions under which the package sustains damage that is equivalent to that from a severe but credible transport accident [SSR-6 paras. 726-737].
- 3.18 Dose rates following Accident Testing should be demonstrated in the PDSR for all Type B and Type C packages.
- 3.19 Dose rates must be shown to not exceed 10 mSv/h at 1 m from the surface of the package with the maximum contents that the package is designed to contain. [SSR-6 paras. 659(b), 671(b)].

4. RELEVANT STANDARDS AND GUIDANCE

- 4.1 For guidance on how transport permissioning assessments are undertaken see 'Transport Permissioning Assessment' TRA-PER-GD-001 [3].
- 4.2 Guidance concerning ONR expectations in the production of a PDSR can be found in 'Guidance for Applicants for UK Competent Authority Approval' TRA-PER-GD-014 [4].
- 4.3 Guidance concerning the international transport standards SSR-6 can be found in SSG-26 'Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)' [2].
- 4.4 A separate TAG on the assessment of nuclear licensees' arrangements for radiation shielding (NS-TAST-GD-002) is available, which focuses predominantly on applications for new facilities [5].
- 4.5 For more information on the Competence of Safety Case / PDSR authors see the Technical Assessment Guide 'Training and Assuring Personnel Competence', NS-TAST-GD-027 [6].
- 4.6 During the ONR assessment, consideration should be given to the 'Regulators' Code' [7].

5. RELATIONSHIP TO ENFORCEMENT POLICY & ALARA

- 5.1 The ONR Enforcement Policy Statement (EPS) stipulates 5 key principles of enforcement that can be applied to PDSR assessment. Further guidance is given in the ONR 'Transport Permissioning Assessment' guidance TRA-PER-GD-001.
- 5.2 *Targeting* – considers which assessments or other regulatory contacts should take priority according to the nature and extent of risks posed by a duty holders' operations. The duty holders' 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 shielding assessment of all package applications and the judgement of the inspector should be used to determine whether a full assessment is required, individual components of a shielding assessment should be analysed (and to what extent) or a broad overview of the shielding assessment will suffice. This can depend on several factors including regulatory knowledge of the applicant and 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* – Duty holders managing similar risks expect a consistent approach from enforcing authorities in the advice tendered; the use of enforcement notices, approvals etc; 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 PDSRs so that package design shielding assessments adopt a consistent approach.
- 5.5 *Accountability and Transparency* – ONR is accountable for our actions. This guidance describes clear standards and is published on the ONR website, giving duty holders sight of PDSR submission expectations with regards to shielding assessment.
- 5.6 *ALARA* - Health and safety duties with respect to package design are specific and absolute. Others *operational duties* require that protection and safety shall be optimized in order that the magnitude of individual doses, the number of persons exposed and the likelihood of incurring exposure shall be kept ‘as low as reasonably achievable’ (ALARA) (SSR-6 para. 301). Enforcing authorities should apply the principle of proportionality in relation to both kinds of duty. Whilst reducing risks ‘as low as reasonable achievable’ is not required during transport package design (the responsibility of the applicant is to ensure compliance with prescriptive regulations), consideration to the ALARA principle may be made during inspections of duty holder transport operations. Where duty holders must control risks ‘as low as reasonably achievable’, enforcing authorities considering protective measures taken by duty holders must take account of the degree of risk on the one hand, and on the other the sacrifice, whether in money, time or trouble, involved in the measures necessary to avert the risk. Unless it can be shown that there is gross disproportion between these factors and that the risk is insignificant in relation to the cost, the duty holder must take measures and incur costs to reduce the risk.

6. ADVICE TO INSPECTORS

General

- 6.1 Inspectors should use a risk-based, targeted approach to determine the amount of effort spent in assessing each PDSR based on a number of factors including: the level of hazard presented by the package, the complexity of the package design and package contents, the safety margin provided by the package design with the worst case radioactive content, the uncertainty of this safety margin, and prior knowledge of the applicant’s competence. A consistent approach to assessment should be adopted depending on the variables described above.
- 6.2 Inspectors might expect to see a wide range of assessment methodologies (e.g. reasoned argument, hand calculations, simple or complex calculations, measured/empirical data or a combination of these) from one assessment to another, based on a hierarchy. The methodology adopted by the applicant should be appropriate to the complexity of the contents and design, the safety margin between the dose rates and the regulatory criteria, and the associated uncertainty of this margin. As a guide, this hierarchy is demonstrated in Appendix 2.

- 6.3 The ONR shielding inspector should expect duty holders to submit a complete and robust safety case. If an inspector considers that evidence required to demonstrate compliance is missing, they should request further evidence from the applicant. However, inspectors may choose to carry out their own calculations, or contract Technical Support Contractors (TSCs) to carry out more complex analyses. Depending on the complexity of the design, simple MicroShield (for gamma cases) or hand calculations may provide some reassurance of compliance with the regulations. More complex designs, designs containing radioactive contents that cannot be predicted using simple methods (such as neutron or secondary gamma radiation) or those with small safety margins may require Monte Carlo or other mathematical models. Calculations carried out by ONR or their contractors should only be used to provide confidence in the package design; they should complement the applicant's calculations but should **not** be used to enhance the case or provide the only evidence to demonstrate compliance for scenarios that are not addressed in the applicant's safety case. The ONR inspector should be a suitably qualified and experienced person (SQEP) to undertake the shielding calculations that may be required to complement the application or should seek assistance from a SQEP ONR inspector or external contracting organisation.
- 6.4 All of the safety features of the package design should be specified in the PDSR or its appendices, and should not only be specified in the operating instructions, or elsewhere. If there are various options that form part of the package, for example, options for the internal furniture or the contents, the specifications and dose rate assessments for each configuration should be included in the PDSR or appendices. Alternatively a bounding case or a number of bounding cases (to bound different conditions of transport) could be defined, as long as it is justified in terms of potential contents.
- 6.5 The ONR inspector should make use of the discipline knowledge within the ONR team working on the same package design. For example, the ONR engineering inspector should be able to determine if the correct mechanical testing was carried out for maximum damage (with respect to the shielding assessment), and analyse the impact of that damage e.g. shine paths caused by material fracture or lead slumping etc. The criticality inspector may be able to provide advice about the neutron multiplication for neutron-emitting radiation sources, noting that the criticality assessment usually assumes more pessimistic scenarios than is necessary for the shielding assessment and that the worst case for criticality assessments is often not the worst case for shielding assessments. The shielding inspector should not assume that inspectors from other specialisms will understand the considerations necessary for shielding assessments, e.g. the worst case scenario that will challenge the shielding case, but it is important for the shielding inspector to engage with the engineering and criticality inspectors, who may have a more detailed understanding of the technical issues related to their disciplines.

Assessing the Applicant's Demonstration of Compliance

- 6.6 Inspectors should look for evidence of a systematic approach within the shielding safety case. For example, when looking at how the bounding case is defined, inspectors should look for the following.
- Evidence of consideration of all packing contents/configurations (for RCT) or reasonably foreseeable conditions (for ACT).
 - Explanation of, and/or quantification of, all assumptions or pessimisms. Inspectors should look for a systematic approach to applying any pessimisms or assumptions so that, for example, the effect of one

simplification does not outweigh the effect of a large number of minor pessimisms. Quantification is generally necessary when uncertainties are large or not well defined by an explanation.

- 6.7 A graded approach should be applied to the demonstration of compliance, depending on the expected safety margin between actual dose rates and the regulatory limit. If pessimisms are applied and compounded (in order to simplify calculations as dose rates are expected to be well within the regulatory limit), there should be some consideration made to the quantifying the pessimisms in order to give an understanding of the expected safety margin.
- 6.8 The graded approach implies that low hazard (*with respect to external package dose rates*) packages may require a less comprehensive assessment, utilising relatively simplistic methods of demonstrating compliance with the appropriate regulations. More complex methods and tools may be required where safety margins are lower due to the increased accuracy they afford.

Source Term Generation

- 6.9 Source term generation is a key aspect in the demonstration of compliance with dose rate design criteria. Without an accurate estimate of the radioactive contents of the package, dose rates calculated in the assessment may be meaningless. The ONR shielding inspector should ensure that the applicant has developed an appropriate source term that bounds the radioactive material to be transported during the lifetime of the certificate of approval.
- 6.10 All appropriate reactions and radiation types should be considered. For example, if the package is designed to transport single gamma emitting radionuclides then the method of source term generation will depend on this, and simple calculations / tools can be undertaken / used to determine the maximum radioactive content. If the package contained, for example, mixed oxide fuel, then a full understanding of the gamma and neutron spectrum associated with the plutonium isotopes, spontaneous neutron emissions, secondary radiation associated with neutrons and alpha particles, etc. should be considered in the source term generation calculations. Secondary radiation produced in shielding materials may also need to be considered. Applicable types of radiation required in transport assessments are covered in Appendix 3.
- 6.11 In considering the validity of shielding calculations, ONR shielding inspectors should seek assurance that the source terms used are adequately and conservatively characterised in terms of isotopic mixture and activity levels, bearing in mind possible factors that could lead to the accumulation of activity, and the physical and chemical form of the source material.
- 6.12 During source term generation, the history of the source may need to be considered. For example, if the source has been irradiated then this should be accounted for, taking consideration of factors such as pre-irradiation storage time, burn-up, cooling time, separation factors and decay time. Codes such as FISPIN and ORIGEN can be used to estimate the source term in such cases.
- 6.13 ONR shielding inspectors should account for daughter nuclides that could significantly affect dose rates. *For example*, if plutonium oxide produced from reprocessing spent fuel is stored for a number of years then there will be associated decay products contributing to dose rates. If the plutonium isotopic mix is known then the source should be reverse-aged (based on the in-growth of Am-241) and decayed using a suitable computer code that will incorporate these decay products (Pu-236 is often

omitted due to it being a trace value, however the gamma radiation from decay products can significantly impact dose rates). As the parent nuclide decays away, daughter products may become more significant. If the source is a single radioisotope then the daughter products of the parent nuclide may need to be considered if the source has been stored for a significant amount of time.

- 6.14 Consideration should be made to time dependence of the source term as the nature of the source may change during the approved package usage period. Radioactive decay effects can in certain circumstances have an adverse effect on the neutron and/or gamma source term. For example, the gamma-ray source strength of a Pu-241 source will increase over time (up to around 70 years after production) due to the ingrowth of Am-241, which is an intense source of low-energy (60 keV) gamma-rays. Another important radioisotope seen in transport assessments that has a significant time-dependence is U-232, which has a high energy daughter product (Tl-208) that in-grows and peaks at around 10 years, double the typical approval period of 5 years.
- 6.15 Trace elements may need to be considered in the shielding assessment. It should be noted that although radioisotopes are present in quantities of parts-per-million or less, they can significantly contribute to or even dominate external dose rates. Examples include; the artificial uranium product U-232 (produced during irradiation and present in trace values only) that has a high energy gamma associated with one of its decay products (Tl-208), traces of Pu-236 in plutonium mixes that have the same high energy gamma issue (this becomes more apparent in well-shielded cases) and fission products that remain in the source following chemical separation.
- 6.16 Enrichment of fissile isotopes in nuclear material should be considered. For example, enriching U-235 in uranium or enriching the fissile ratio of MOX fuel. This can have adverse or favourable effects on external dose rates depending on fuel and radiation type. The enrichment of trace products should also be considered where appropriate. For example, enriching reprocessed uranium will not only increase the fissile content, but also the lighter radioisotopes such as U-232 and U-234, which can significantly affect dose rates.
- 6.17 Consideration should be given to neutron multiplication in individual sources or arrays of sources where fissionable materials are present. If these factors are calculated using criticality codes then the neutron multiplication factor from an output that best represents the realistic shielding scenario should be used. However, if compliance can be demonstrated with the maximum multiplication factor then this may be used instead.

Geometry Modelling

- 6.18 If calculations are being undertaken, simplifications and approximations may be made to the geometry. These approximations should be defined depending on the effect they could have on external dose rates and the safety margin expected in calculations. For example, where safety margins are expected to be high, shielding layers and / or weaknesses (e.g. steel screws in lead shielding) may be smeared or ignored for simplicity. Some of the more detailed design components may be removed if they are not expected to significantly affect external dose rates. The reasons for these omissions should be explained and justified in the shielding assessment. This may not be appropriate where safety margins are low.
- 6.19 The geometry of radioactive sources can range from a single nuclide tending to point sources, to very large, complex multi-radioisotope / radionuclide sources. There are many factors to consider if the source is to be approximated to either a simplistic point

source or a smeared source, such as self-shielding, change in distance fall-off, re-distribution of activity away from weaknesses in the package, the neutronics of the system, increase / decrease of oblique angle shielding, etc. It cannot always be assumed that modelling the activity of a point source will give the most pessimistic dose rate in all scenarios. However, modelling the source exactly is not always required and a judgement shall be made as to the extent of detail required in source modelling.

- 6.20 Features of the packages that provide shielding weaknesses will require consideration. For example; lifting trunnions, the lid/package interface, venting systems, drain points, seals, etc. can present localised dose rate hot-spots.
- 6.21 Shielding tolerances, densities and material composition may need to be considered. The density of shielding materials should be accurately modelled. The density of the source material should be determined and if a range of densities is to be used then the worst case should be considered, noting that density changes can impact external dose rate due to self-shielding, neutronics (neutron multiplication), oblique angle shielding (due to volume increases), etc. Where specific shielding material is being used then the exact material composition may need to be modelled. For example, antimony in lead alloy will reduce the effectiveness of shielding quite significantly when compared with 100% lead. Various types of shielding that may be considered in transport assessments are discussed in Appendix 4. This is a non-exhaustive list.
- 6.22 Dose points should be modelled at the appropriate locations. If scoring / tally bodies are used to score particles (in order to calculate dose rates), then appropriately sized bodies should be used, with potential underestimations due to averaging effects (as a result of large scoring / tally body size or localised weaknesses) accounted for.

Use of Codes

- 6.23 The applicability of radiation source term generation or shielding methods may be determined by the level of safety margin expected. Shielding assessment can take the form of reasoned argument and/or use of empirical data, through to hand calculations and/or complex stochastic or deterministic shielding codes.
- 6.24 If source term generation and shielding codes are used in the assessment, then the shielding assessor should be suitably qualified and experienced to use the code. The ONR shielding inspector may wish to see the shielding assessor's training records and evidence of experience.
- 6.25 An appropriate version of the code should be installed with relevant data libraries, response functions, etc. noting that developmental changes and/or changes to library data may have an impact on the calculated dose rates. The ONR shielding inspector should be confident that the library data used in codes is suitable for the application. For example, if continuous energy spectra are grouped into a single energy group, it should be ensured that key radionuclides are placed in appropriately sized energy groups. For example, due to the group structure of FISPIN the contribution of 60 KeV Am-241 gammas to the dose rate will be overestimated at 75 KeV and as such, the group may require restructuring.
- 6.26 It should be ensured that the code has been installed and validated correctly.

Assessment of Routine Conditions of Transport (RCT)

- 6.27 Assessment should be carried out in accordance with sections 3.1 to 6.26 and 6.28 to 6.33.
- 6.28 The criteria for RCT are discussed in sections 3.4 to 3.13.
- 6.29 The maximum package surface dose rate should be calculated assuming the maximum contents, taking into account all sides of the package and any shielding weaknesses.
- 6.30 The source should be calculated as discussed in sections 6.9 to 6.17.
- 6.31 Package weaknesses should be accounted for as discussed in sections 6.18 to 6.22.
- 6.32 Applicants can submit dose rate survey data as evidence of compliance for packages that are already operational. Evidence of appropriate and thorough surveys should be provided to give reassurance that any shielding weaknesses have been considered. If the source/package used in the dose rate survey is different to the source/package in the PDSR, then the applicant must assure the ONR shielding inspector that the survey source is suitably representative.
- 6.33 For the dose rates around a conveyance or vehicle, shielding in the vehicle may be taken into consideration. Where information about the vehicle, or the number of packages to be transported is not known by the applicant, conservative assumptions can be made. For example, assumptions of; the smallest vehicle that could be used (eg standard ISO, heavy goods vehicle, light commercial vehicle), the maximum number of packages to be transported in each load, and the 'worst case' loading configuration can be made to demonstrate that compliance with the regulations has been considered at the design stage.

Assessment of Normal Conditions of Transport (NCT)

- 6.34 The NCT dose rate criteria are discussed in 3.15.
- 6.35 The increase is to the *maximum* surface dose rate. For example, if the highest dose rate calculated at any one point on the package surface is 1.5 mSv/h, then the highest dose at any position on the package surface following NCT tests must not exceed 1.8 mSv/h. If the highest dose rate calculated at any one point on the package surface is 1.0 mSv/h, then the highest dose at any position on the package surface following NCT tests must not exceed 1.2 mSv/h. See Figure 1 below.

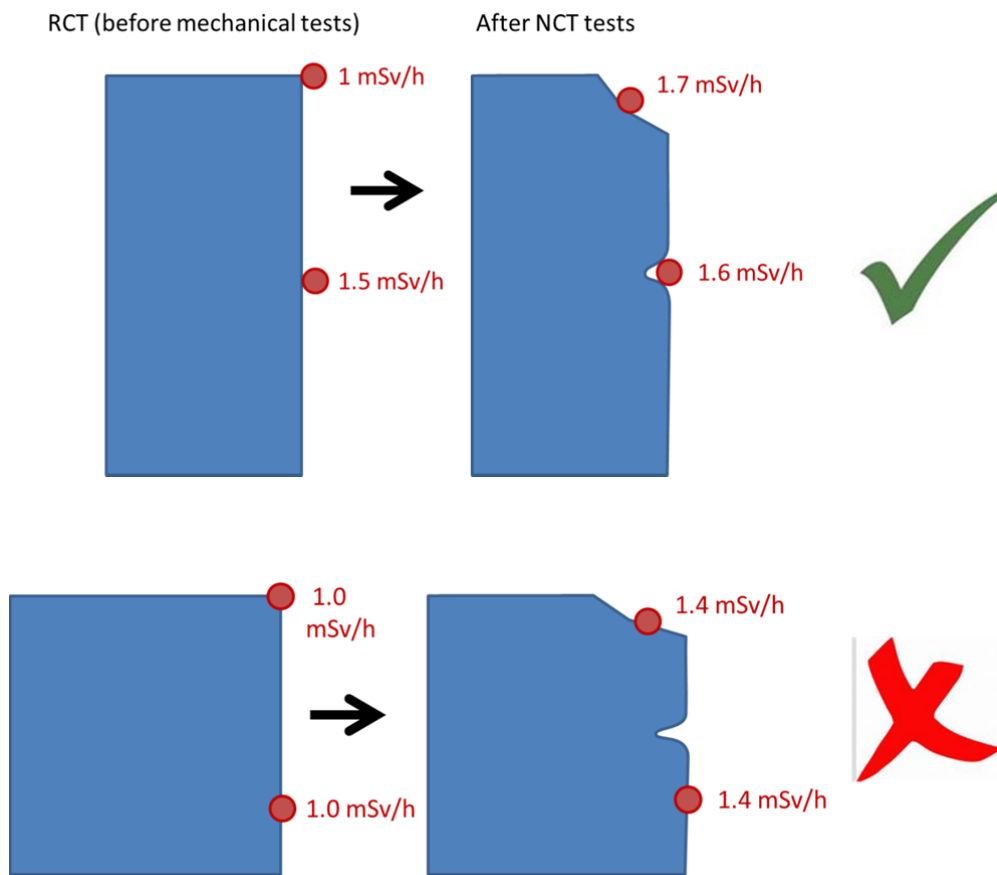


Figure 1: Example changes in package surface dose rate from Routine Conditions of Transport to Normal Conditions (following Normal Condition tests). The top example of change is acceptable, whereas the bottom example does not meet the regulatory requirement.

- 6.36 If a pessimistic bounding case has been used to demonstrate compliance with routine conditions of transport (with respect to source geometry and location), then it may not be acceptable to consider this as the basis of the NCT 20% increase. The purpose of the regulation is to prevent actual significant increases during transportation and as such the baseline dose rate used before the NCT tests should be one calculated in a realistic loading configuration. In certain scenarios it may be beneficial to use a number of different methods to demonstrate compliance with the 20% NCT regulation as described in 6.46 to 6.50.
- 6.37 The relevant testing is discussed in sections 3.14 to 3.16.
- 6.38 The rationale for testing parameters (whether tested, or not) should be clearly set out, or referred to in the shielding safety case. For example, drop orientations and internal packing arrangements which cause the maximum damage should be explained, and creation of any shine paths should be considered, alongside any other potential for damage to the shielding from physical impact.
- 6.39 The ONR shielding inspector may wish to consider the results of the NCT test reports when considering the applicants assumptions in the shielding assessment.

Alternatively, the ONR shielding inspector may consult with the relevant engineer to provide a judgement on the applicant's assumptions.

- 6.40 If test models are used, they should accurately represent the intended design, including the contents which should represent the actual contents in mass, density, composition, volume and any other relevant characteristics. Where there are differences in the test model or contents, these should be fully explained and an analysis provided which assesses any differences from the test outcomes.
- 6.41 Good practice to demonstrate compliance via testing might consist of a description and photographic evidence of any damage, or otherwise, to the package shielding or its components; or damage to, or movement of, any internal furniture (holding the sources in place) or sources (or surrogate sources).
- 6.42 Of the NCT tests, the drop test will usually have the most significant impact to the external dose rate. Account should be taken of:
- damage to / displacement of the source (in particular if the source moves closer to any shielding weaknesses)
 - damage / movement to the furniture / cavity internals
 - damage / movement to the packaging
 - damage / movement to any internal shielding arrangements
 - any changes in neutron multiplication due to the above.

These should all be considered when demonstrating compliance with NCT criteria.

- 6.43 Once evidence of the NCT testing has been demonstrated, compliance with the NCT criteria can be demonstrated by the methods discussed below.
- 6.44 Compliance with the NCT criteria can be demonstrated by one or more of the following:
- **Comparison to a similar package** that has been subjected to the NCT tests (where it can be justified that the packaging and contents are bounded by the tested package);
 - **Reasoned argument;**
 - **Calculation** (e.g. Monte-Carlo calculations).

Where it is difficult to demonstrate compliance with the techniques described above (for example where the source is not well defined or for packages containing waste), the applicant may use additional methods (as part of a wider justification - see 6.49) such as:

- **Measurements;**
 - **Operational Use.**
- 6.45 **Comparison to a similar package** - If the package is similar to and bounded by a package that has already been tested, this can be used as evidence of compliance. It must be demonstrated, however, that the package *is* actually bounded by the tested package and that the differences would not adversely affect the outcome of the test results.
- 6.46 **Reasoned argument** may be used to demonstrate compliance with NCT criteria. For example, if a visual inspection shows that the testing had an insignificant effect on the package (with regards to section 6.42) then this can be presented as evidence of

compliance, i.e. evidence of no damage or movement of internal components, no damage or movement of the sources themselves and no damage to the outside of the package.

- 6.47 **Calculation** - If there has been significant change (with regards to section 6.42) then radiation shielding calculations may be required to determine what the increase in dose rate would be post-NCT testing. For the pre-damaged calculations the source should be modelled in a realistic loading configuration (see 6.36) and the post-testing calculation should take into account the conditions in 6.42.
- 6.48 **Measurements** - (historical / survey / comparison with similar package – see 6.46) can be used to determine the increase in surface dose rate following NCT testing, but it should be borne in mind that: 1) account should be taken of damage / displacement of the source, not just damage to the packaging; and 2) measurements may not provide confidence that the increase is less than 20% due to measurement errors, background dose rate and other environmental differences. **Measurements should only be used as part of a wider justification.**
- 6.49 **Operational Use** - SSG-26 guidance for NCT conditions relating to external package dose rates does not make allowance for how the package will be operated. However, **as part of a wider justification**, the applicant may account for; the likelihood of an NCT event occurring during transport and the consequences of this on dose uptake, consideration of remediation following an NCT event and historical evidence demonstrating that there have been no significant increases in surface dose rates in previous transportations (i.e. comparing dose rates at dispatch and receipt, although it should be noted that there may be no evidence of an NCT event occurring).
- 6.50 Any combination of the above methods may be used to provide a robust demonstration of compliance with the NCT criteria. The arguments should be presented coherently. More guidance can be found in SSG-26.
- 6.51 If the package contents are fissionable, any damage or movement of the source which could impact on the neutron multiplication should be explained. The ONR criticality inspector or the criticality sections of the package safety case may be able to provide useful information. However, it should be noted that the criticality assessment tends to apply more pessimistic assumptions.
- 6.52 ACT tests may be used to bound the impact of damage from NCT tests, however the 20% surface dose rate increase condition for NCT may not be demonstrated by the ACT tests and may need to be tested, calculated or explained separately.
- 6.53 If a package is designed to carry a number of different contents (including source holders, furniture, etc.), one way to demonstrate compliance with NCT conditions is with the definition of a bounding case. This should represent the 'worst case' source (or sources) under 'worst case' control within the package. The ONR shielding inspector should check that the bounding case is fully justified for all the potential contents. If a package is designed to carry bounding case contents, this should have been characterised in enough detail to inform one or more definitive designs, including of internal furniture, even if a number of options are possible.
- 6.54 The bounding case should usually consider:
- the radionuclides and/or specific activity and/or activity concentration, location of activity in the source and number of sources;

- source and source-containing-item size, mass, and geometry, and consideration of whether this could impact on other safety criteria including but not limited to whether there are any sharp or protruding features that could damage the internals of the package, whether hydrolysis or radiolysis could occur, or whether the bounding case adequately considers any impact on the packing arrangement or the components used to secure the source;
 - the source material composition.
- 6.55 In some cases it may be necessary to reference or include these bounding conditions on the transport certificate if there is some uncertainty about the nature of the source or how it is held in the package.
- 6.56 If the package describes a bounding case and gives the consignor the opportunity to change the contents (not necessarily with respect to radioactive contents, but source furniture) then the applicant must retain control of any changes to the contents that the consignor may wish to make. For example, if the contents are not as defined in the PDSR (in terms of geometry, mass, etc.), the consignor must check with the design authority whether the contents change is within the bounding case. The design authority should have systems in place (discussed in the safety case) to assess any deviations from the bounding case and record any decisions. If the decision is that the new contents are not within the bounding case, a competent authority approval to the modification will be required. It should be noted that any proposed modification in the furniture/internal contents will need to be considered in terms of the effects on the thermal/impact performance, which may in turn impact on the criticality safety and shielding performance of a bounding case.
- 6.57 For general purpose packages, the applicant may choose to define specific contents and submit any future changes to the competent authority as modifications, whereby only the changes from the previous design will be assessed.
- 6.58 SSG-26 section VII, [SSG-26 paras. 701 and 702] sets out further guidance on testing and calculations to demonstrate compliance for NCT.

Assessment of Accident Conditions of Transport (ACT)

- 6.59 The ACT dose rate criteria are discussed in 3.19.
- 6.60 The relevant testing is discussed in sections 3.17
- 6.61 Demonstration of compliance with ACT criteria can be demonstrated by applying the same consistent rationale as described in sections 6.38 to 6.58.
- 6.62 It can often be shown using relatively straightforward calculations that dose rates for Type B and Type C packages will meet the ACT criteria.
- 6.63 The mechanical and thermal tests are more likely to have a significant effect on the package integrity with regards to external dose rates.
- 6.64 The type of damage that is likely to lead to external dose rates that will challenge the ACT criteria usually includes (but is not limited to):
- the creation of shine paths due to damage / displacement of shielding material following mechanical testing (e.g. displacement of materials including lead slumping);

- melting of shielding material following the thermal test;
- burn off of hydrogenous shielding material following the thermal test.

6.65 It is not uncommon for the shielding assessor to make pessimistic assumptions that bypass the test results and require more simple calculation and less reasoning, for example, assuming that all hydrogenous neutron shielding is lost following the fire test.

Validation, Verification and Peer Review

- 6.66 The inspector may wish to check that the code used has been correctly validated.
- 6.67 Depending on the safety margin between calculated results and dose rate criteria, there may be cases where verification is required. Calculations using computer codes may be cross-checked by the shielding assessor independently, especially if the safety margin is small. Using survey data, hand-calculations etc. may serve as an appropriate verification, and can provide additional confidence in calculated results. The shielding assessor should take a graded approach when deciding on the appropriate verification method.
- 6.68 If the cross-check does not agree with the primary calculation, then this may be acceptable providing a justification is provided and differences are clarified. Generally, cross-checks will be performed using a less complex code (or hand calculation) with some modelling and source simplifications, and as such, differences within a factor of 2 are generally acceptable if they can be explained.
- 6.69 If hand calculations were used to demonstrate compliance and there is no simple way to cross-check, then a comparison may be made to similar work or a similar package designs to show consistency.
- 6.70 Independent cross-checking of the source term is not always required, but there should be some evidence that the assessor is confident that the source term to be used in the shielding code is accurate and bounding.
- 6.71 In some circumstances it may be necessary to perform a completely independent cross-check using a different calculation method / code and rebuilding the geometry. This may be dependent on the safety margin and complexity of the design. For example, where acceleration techniques have been used in Monte-Carlo codes, the assessor may wish to cross-check using a deterministic code if the safety margin is low. This should be judged on a case-by-case basis.
- 6.72 Shielding assessments should be peer reviewed before submission.
- 6.73 In certain cases, it may be required that the applicant performs an Independent Nuclear Safety Assessment (INSA), but this should be agreed during early engagement where appropriate.
- 6.74 ONR Shielding Inspectors may need to get their work peer reviewed by a fellow inspector, where deemed appropriate. Further information on this can be found in the ONR Transport Permissioning Process Guide TRA-PER-GD-001.

Quality and Competence

- 6.75 Changes to the shielding design over time should be managed and recorded. These should be clearly catalogued in the PDSR and/or within the applicant's management system. All changes since the previous application should also be described in full.

- 6.76 Inspectors should check that the key sections of the PDSR and related supporting documentation relevant to the shielding safety are appropriately linked and properly referenced. It should be ensured that any stipulations related to the shielding safety (such as activity limits and operational requirements) are consistent in the overarching safety document, supporting safety documentation and the certificate issued by ONR.
- 6.77 Inspectors may seek maintenance or inspection records that relate to package shielding. This might be done, for example, to seek reassurance that certain design features have not changed over time due to material degradation or wear and tear etc.
- 6.78 Inspectors should consider whether the appropriate methodology has been selected to demonstrate compliance with dose rate limits (see Assessment hierarchy – Appendix 2). Inspectors should expect that a review of shielding assessment should be carried out for Type B and Type C packages at least every five years, with a review of the methodology to ensure that current codes, nuclear data, methods are being used and that there have been no significant changes to regulations that could impact the shielding assessment (note that this does not mean a full shielding review is required every five years).
- 6.79 The case 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 or extrapolated information is substantiated.
- 6.80 In accordance with 6.67, calculations may require cross-checking by the shielding assessor, and/or verifying by another method.
- 6.81 Any instructions that are applicable to ensure compliance with any regulation should be clearly stated in the relevant documentation. For example, if there is an important radionuclide limit to ensure safety (that has been calculated in the supporting shielding document), this should be stated in the relevant contents document, PDSR and certificate of approval (if required). If there are loading / packing / handling requirements for shielding compliance then these must be clearly stated in the relevant documentation. The safety case should self-consistent and coherent.

7. RECOMMENDATIONS FROM THE SHIELDING ASSESSMENT

- 7.1 If a shielding safety case is compliant with SSR-6 requirements, any shortfalls are insignificant and the ONR shielding inspector is confident that the package design is safe and meets the applicable regulations, the ONR shielding inspector should recommend that a five year certificate is issued. Tier 2 advice (not directly related to the safety of the package) may be issued on the assessment record (Q1AR) (in accordance with the transport permissioning guidance) alongside the certificate if minor issues that do not directly impact on safety have been identified during the assessment. The ONR shielding inspector should make a record of any tier two comments to follow up in advance of future assessments.
- 7.2 For packages that have been previously approved by ONR and where the latest application contains safety significant shortfalls (but the ONR shielding inspector is confident that the previously approved package design is safe and meets the transport regulations), the ONR shielding inspector can recommend that a short term one year certificate is issued. This may be appropriate if, for example, supporting evidence is not documented or there are incorrect assumptions in calculations, but the ONR shielding inspector is confident that the actual package design is safe and meets the transport regulations, e.g. there are self-evident safety margins or the ONR shielding

inspector has carried out confirmatory calculations. The purpose of the short term certificate is to allow continued transport operations whilst the applicant provides documentary evidence of compliance with RCT, NCT and ACT in the shielding safety case. An extension is not the licensing of a non-compliant package.

- 7.3 In either case (5-year or 1-year recommendation), the ONR shielding inspector may recommend that additional limits or restrictions are put on package use, to be stated on the certificate. These should be discussed with the applicant in advance of issuing the certificate.
- 7.4 If the ONR shielding inspector believes there to be safety significant shortfalls in the shielding safety case and has no confidence that the package design is safe and meets the transport regulations, then the ONR shielding inspector should recommend that the applicant resubmits the application. This may be because, for example, supporting evidence is not documented, incorrect assumptions outweigh safety margins, or if the ONR shielding inspector's own calculations do not demonstrate compliance with the applicable regulations.

8. THE UK SHIELDING FORUM (TSF) AND TRANSPORT CONTAINER STANDARDISATION COMMITTEE (TCSC)

- 8.1 ONR shielding inspectors should be aware of the 'UK Shielding Forum' (TSF), a non-executive national committee with members from organisations which are concerned with shielding and radiation transport through matter and the 'Transport Container Standardisation Committee' (TCSC). The UK Shielding Forum interacts with the UK Working Party on Criticality (WPC) and the UK Nuclear Science Forum (UKNSF). ONR's specialist inspectors are encouraged to familiarise themselves with current shielding developments and good practice as discussed by TSF and TCSC Codes of Practice.

9. REFERENCES

1. SSR-6 'Regulations for the Safe Transport of Radioactive Material (2012 Edition)'.
2. SSG-26 'Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)'.
3. 'Transport Permissioning Assessment', TRA-PER-GD-001.
4. 'Guidance for Applicants for UK Competent Authority Approval', TRA-PER-GD-014.
5. ONR TAG 'Radiation Shielding', NS-TAST-GD-002
6. ONR TAG 'Training and Assuring Personnel Competence', NS-TAST-GD-027.
7. Regulators' Code, <https://www.gov.uk/government/publications/regulators-code>

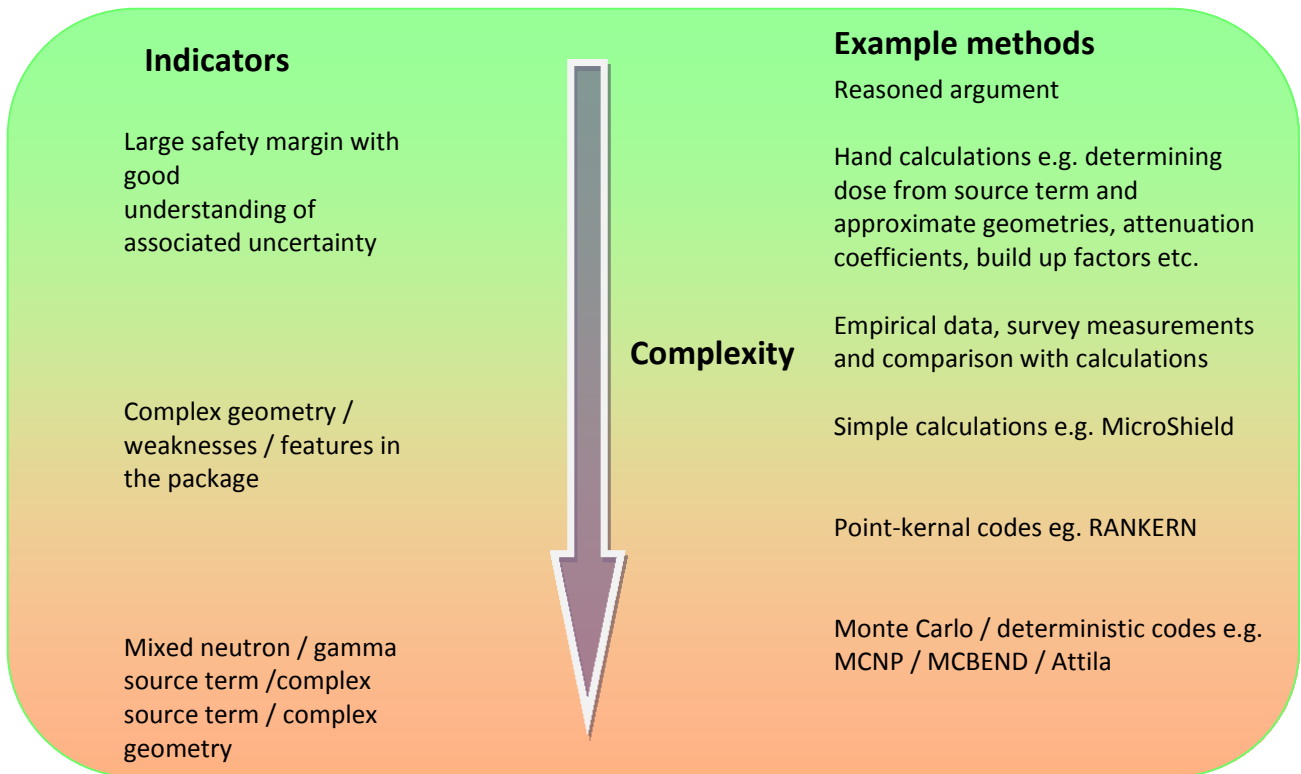
10. APPENDICES

Appendix 1 List of package and Conveyance Dose Rate Criteria from SSR-6

SSR-6 Para. No.	PACKAGE Dose Rate Criteria (NB. some of these are not design requirements)	Radiation level limit (mSv/h)
516	Radiation level at any point on the external surface of an excepted package	0.005
517	Quantity of LSA (Low Specific Activity) or SCO (Surface Contaminated Object) in a IP (Industrial package) or object or collection of objects shall be so restricted that the external radiation level at 3 m from the unshielded material or object or collection of objects does not exceed 10 mSv/h.	10
527	Radiation level at any point on any external surface of a package (when not transported under exclusive use by road or rail, or under both exclusive use and special arrangement by vessel or air)	2
528	Radiation level at any point on any external surface of a package (when transported under exclusive use)	10
573(a)	Radiation level on external surface of a package (when transported under exclusive use) by road or rail may only exceed 2 mSv/h, and must be kept below exclusive use limit if, and only if, (1) the vehicle is equipped with an enclosure, (2) the position of package in vehicle remains fixed during routine transport, and (3) there are no loading or unloading operations between beginning and end of the shipment	10
Table 10, Footnote (a)	Radiation level on any external surface of a package when being transported under exclusive use in or on a vehicle may be transported by vessels provided they are not removed from the vehicle at any time while on board the vessel	10
575	Radiation level on any external surface of a package when being transported by a vessel: - Not under special arrangement - Under special arrangement	2 >2
579	Radiation level on any external surface of a package when being transported by air: - Not under special arrangement - Under special arrangement	2 >2
526	Radiation level 1 m from any external surface of a package not transported under exclusive use (established implicitly using TI)	0.1
648	Radiation level on any external surface of a Type A package following exposure to the normal conditions of transport tests	<20% increase from design level
659	Radiation level 1 m from any external surface of a Type B package following exposure to accident-simulating tests	10
671	Dose rates following Type C accident testing	10

SSR-6 Para. No.	CONSIGNMENT Dose Rate Criteria (NB. some of these are not design requirements)	Radiation level limit (mSv/h)
513	Conveyances which have become contaminated must be decontaminated such that radiation levels at surfaces of conveyance from fixed contamination must be below limit	0.005
566(b)	For non-exclusive use, radiation levels at any point on the external surface of the conveyance	2
573(b)	For exclusive use, radiation levels at any point on the external surface of the conveyance	2
566(c)	For non-exclusive use, radiation levels at 2m from vehicle	0.1
573(c)	For exclusive use, radiation levels at 2m from vehicle (vertical planes)	0.1

Appendix 2 Assessment Hierarchy



NB. Quite often, it is relatively easy to calculate dose rates for simple problems using complex tools.

Appendix 3 Radiation Types applicable to Transport Assessment

This note provides guidance on the types of ionising radiation that may need to be considered in transport shielding assessments. Note that alpha particles do not present an external radiation hazard since they are only very weakly penetrating and are stopped by the outer dead layer of the skin. However, alpha emission can give rise to other types of ionising radiation, e.g. gamma rays and neutrons, that do present an external radiation hazard and these effects are covered in this note. (It should be noted that alpha particles represent a major internal radiation hazard and so high standards of containment are required where mobile alpha emitters are present, e.g. plutonium oxide powder.)

Beta Particles and Bremsstrahlung

Beta particles are rapidly moving electrons, emitted when a neutron inside a nucleus is transformed into a proton. This commonly occurs in neutron-rich nuclei. The energies of the electrons emitted by commonly occurring beta emitters are typically up to around 2 MeV.

The electrons exhibit a continuous energy spectrum, from zero up to the total energy associated with the decay. The mean beta particle energy is typically between 30% and 40% of the maximum, which is equal to the total energy associated with the decay.

As with all types of ionising radiation, the penetrating power of beta particles increases as their energy increases. Higher energy beta particles can penetrate the outer dead layer of the skin and so can give rise to an external radiation hazard. However, beta particles are generally relatively easily shielded and, for commonly occurring beta energies, are stopped by a few mm of dense metal. Therefore, the structural and shielding materials associated with many transport packages means that beta particles do not give rise to an external radiation hazard.

As beta particles slow down in matter due to electromagnetic interactions, principally with atomic electrons, they emit electromagnetic radiation known as Bremsstrahlung (“braking radiation”). This type of radiation is emitted with a continuous spectrum, from zero up to the maximum kinetic energy of the beta particle. Note that Bremsstrahlung has essentially the same properties, and behaves in the same way, as gamma radiation, although the term gamma radiation is strictly reserved for electromagnetic radiation emitted by excited nuclei.

Bremsstrahlung radiation is uncharged and is usually more penetrating than the beta particles themselves and so may sometimes need to be considered in transport shielding assessments.

The fraction of the beta particle energy that is emitted as Bremsstrahlung is usually quite low, up to a few %, but increases non-linearly as the energy of the beta particles and the atomic number of the stopping medium increase. Hence, in cases where Bremsstrahlung is a problem, shielding materials containing atoms with low atomic numbers, e.g. perspex, are often used (in front of metal shielding).

Unlike gamma rays and neutrons, beta particles have quite well defined ranges in matter. (There is some variation known as straggling). It may be possible to use published attenuation curves to demonstrate that they will not present an external radiation hazard. However, in lightly shielded packages where they do present an external radiation hazard, it is generally necessary to use a Monte Carlo computer code to obtain accurate estimates of the dose rates outside the shielding.

The fraction of the beta particle energy emitted as Bremsstrahlung can be estimated using expressions available in standard textbooks on radiation protection. A simple bounding estimate of the dose rate due to Bremsstrahlung can be obtained by assuming all the photons

to have the maximum beta particle energy and using published attenuation curves for photons of the appropriate energy. More detailed calculations will usually require the use of a point kernel or Monte Carlo computer code to model the shielding materials and the Bremsstrahlung with its true spectrum.

Electron Capture Gammas

A proton inside a nucleus can capture an electron from one of the inner atomic orbitals and be transformed into a neutron. The capture of the electron leaves a vacancy in one of the inner atomic orbitals. This vacancy is rapidly filled as electrons from the outer atomic orbitals undergo transitions into the inner atomic orbitals. These electron transitions result in the emission of electromagnetic radiation known as characteristic X rays. The characteristic X rays have discrete energies, determined by the atomic number of the nucleus, which dictates the energies of the excited states.

The energies of the characteristic X rays increase as the atomic number of the nucleus increases. Higher energy characteristic X rays can penetrate significant thicknesses of matter and may need to be considered in transport shielding assessments.

The energies and yields of characteristic X rays can be obtained from standard textbooks on radiation protection (e.g. ICRP 107). Alternatively, they may be contained in data libraries provided with shielding computer codes. For simple cases, dose rates can be calculated using published attenuation curves. For more complex cases, a point kernel or Monte Carlo computer code may be required.

Gamma Rays

Beta particle emission often leaves the daughter nucleus in an excited state. This excitation energy is often emitted rapidly in the form of electromagnetic radiation known as gamma rays, as the daughter nucleus returns to its ground state. Gamma rays are emitted with discrete energies, determined by the numbers of neutrons and protons in the daughter nucleus, which determine the energies of the excited states. The energies of the gamma rays emitted by commonly occurring sources are typically up to around 4 MeV.

When passing through matter, gamma rays interact principally with electrons and the dominant mechanisms for energies up to around 4 MeV are photoelectric absorption (with bound electrons) and Compton scattering (with free electrons). In addition, electron-positron pair production in the electromagnetic field of a nucleus becomes energetically possible for gamma ray energies in excess of 1.022 MeV (twice the rest mass energy of the electron or positron).

Gamma rays can penetrate significant thicknesses of matter and need to be considered in transport shielding assessments. The best shielding materials for gamma rays are materials containing atoms with high atomic numbers, e.g. dense metals such as steel and lead. A monoenergetic, well-collimated beam of gamma rays will be attenuated according to an exponential decay relationship in matter. For example, the mean free path for the 0.66 MeV gamma rays emitted by a Cs-137 source is around 2 cm in steel. However, for deep shields build-up of scattered radiation needs to be considered. This is caused by Compton scatter of radiation back to the dose rate assessment point, including pair production gamma rays. Irradiated reactor fuel contains large quantities of beta emitting fission products and presents a very intense source of gamma rays. Hence, transport flasks for irradiated reactor fuel incorporate significant thicknesses of dense metals to shield the gamma rays down to acceptable levels.

Some alpha emitters also leave the daughter nucleus in an excited state, which may decay by the emission of gamma rays. Hence, although alpha particles themselves do not need to be considered in transport shielding assessments, the gamma rays emitted by the decay of the daughter products may need to be considered.

The energies and yields of the gamma rays emitted by common gamma ray sources can be obtained from standard textbooks on radiation protection. Alternatively, they may be contained in the data libraries provided with shielding computer codes. For simple cases, dose rates can be estimated using published attenuation curves. For more complex cases, it may be necessary to use a point kernel or Monte Carlo computer code.

Internal Conversion

As an alternative to gamma ray emission, the excited states in daughter nuclei produced as a result of beta particle, positron and alpha particle emission may sometimes decay by internal conversion. Here, the excitation energy of the daughter nucleus is transferred to an electron from one of the inner atomic orbitals, which is subsequently ejected from the atom.

Hence, this process gives rise to both rapidly moving electrons and characteristic X rays as the vacancy in the inner atomic orbitals is filled. The ejected electrons have discrete energies, determined by the energies of the excited states in the daughter nucleus and the energies of the states occupied by the orbital electrons. As explained earlier, the characteristic X rays also have discrete energies.

The ejected electrons behave like beta particles (which are also electrons) and may need to be considered in transport shielding assessments. The characteristic X rays may also need to be considered in transport shielding assessments.

Neutrons

The most common sources of neutrons likely to be encountered in transport shielding assessments are produced by spontaneous fission, neutron-induced fission and alpha-neutron reactions, which usually involve low atomic number target nuclei. (Neutron sources based on other reactions may occasionally be encountered, e.g. photoneutron sources, which are based on gamma-neutron reactions, and sources based on spontaneous neutron emission).

Fission involves the splitting of a heavy nucleus into two fission products of unequal mass. The most common mass numbers of the fission products are around 90 and 140. Fission is an energetic process and is accompanied by the emission of beta particles, neutrinos, gamma rays and neutrons.

Some heavy nuclei are sufficiently unstable that they undergo spontaneous fission without any external stimulus. An example of this effect is Cf-252, which is often used to make intense neutron sources for industrial and scientific use.

Alternatively, some nuclei require the absorption of a neutron to undergo fission. Those nuclei that will undergo fission following the absorption of a neutron of any energy are referred to as fissile. Important examples of this effect are U-235 and Pu-239. Alternatively, those nuclei that will only undergo fission following the absorption of a high-energy (> 1 MeV) neutron are referred to as fissionable. An example of this effect is Pu-240.

Each fission event results in the emission of usually 2 or 3 neutrons. The energy spectrum of the neutrons is continuous, with very few neutrons having energies above around 10 MeV. The average energy of the neutrons emitted in fission is typically around 2 MeV.

Neutrons can also be produced by alpha-n reactions. Here, the alpha particles emitted by an unstable, heavy nucleus interact with the atoms of a lighter target nucleus, resulting in the formation of a new daughter nucleus and the emission of neutrons. For example, a mixture of radium and beryllium or americium and beryllium is often used to produce intense neutron sources.

The energies of the neutrons emitted by alpha-n sources depend on which nuclei are chosen to make the source. However, the neutrons typically have a broad spectrum of energies up to around 10 MeV. (The alpha particles and the neutrons are both initially produced with discrete energies. However, the alpha particles are slowed down very rapidly in matter and so have a continuous distribution of energies by the time they interact with the light nuclei. Hence, the neutron energy spectrum is also continuous).

Neutrons can penetrate significant thicknesses of matter and need to be considered in transport shielding assessments. Neutrons interact with atomic nuclei and the best shielding materials for neutrons are materials containing atoms with low atomic numbers, e.g. polythene and wood. Like gamma rays, the attenuation of a monoenergetic, well-collimated beam of neutrons in matter follows an exponential decay relationship. However, neutron sources do not generally emit monoenergetic neutrons and so the attenuation curves are more complex. For the neutrons produced by a fission source, the mean free path is typically between 5 cm and 10 cm in polythene. As with gamma-ray buildup, the build-up of low energy neutrons should also be considered.

Neutron dose rates are generally more difficult to calculate than gamma dose rates since scattering reactions are more significant. For simple geometries, it may be possible to use a discrete ordinates computer code. However, more complex cases are best addressed using a Monte Carlo code.

Neutron shielding may often have a high thermal neutron absorption shield (such as boron) after a low atomic number shield. This is to absorb thermal neutrons produced by scatter within the low atomic number shield.

Secondary Gamma Rays

In addition to causing fission reactions in heavy nuclei, neutrons also undergo several other types of nuclear reaction in matter. Some of these reactions give rise to secondary gamma rays. The two most important examples are inelastic scattering and radiative capture.

Inelastic scattering involves the transfer of some energy from a neutron to a target nucleus. The neutron continues with reduced energy. The target nucleus gains some kinetic energy and is also left in an excited state. The target nucleus may emit gamma rays as it returns rapidly to its ground state. (Note that elastic scattering is also possible. Here, the neutron continues with reduced energy. The target nucleus gains some kinetic energy but is left in its ground state and so does not emit secondary gamma rays).

In radiative capture, the neutron is absorbed by a target nucleus, which is left in an excited state. The neutron no longer exists as a free particle. Again, the target nucleus may emit gamma rays as it returns rapidly to its ground state.

Secondary gamma rays, particularly those produced by radiative capture, tend to have relatively high energies and are not attenuated by the full thickness of shielding materials since they are produced within the shielding materials. Hence, they can be an important source of radiation and may need to be considered in transport shielding assessments. As with neutron dose rates, secondary gamma ray dose rates are generally not simple to calculate. For simple cases, it may be appropriate to use a discrete ordinates computer code. However, for a more complex cases a Monte Carlo or deterministic code will usually be required.

In some cases, it may be appropriate to add some gamma ray shielding outside the neutron shielding to absorb the secondary gamma rays produced within the neutron shielding. Alternatively, a material having a high thermal neutron capture cross section may be added to the neutron or gamma shielding to reduce the thermal neutron flux and thus the potential of secondary gamma ray production.

Activation Gamma Rays

If a neutron is captured by a target nucleus, the product nucleus may itself be unstable, often with respect to beta decay, and is referred to as being activated. When the activated nucleus decays to a more stable daughter nucleus, the daughter nucleus may be left in an excited state, which will often decay to its ground state by gamma ray emission.

An important example of this effect occurs in steels, which generally contain small amounts of Co-59 as an impurity. Under neutron irradiation, the Co-59 captures neutrons to form unstable Co-60. The Co-60 undergoes beta decay with a half live of around 5 years. The Ni-60 daughter nucleus is left in an excited state and decays to its ground state by the emission of 1.17 MeV and 1.33 MeV gamma rays.

Neutron activation may need to be considered in shielding assessments for transport packages where materials have been subject to significant neutron irradiation. As mentioned earlier, the best shielding materials for gamma rays are materials containing atoms with high atomic numbers, e.g. dense metals such as steel and lead.

Summary

Guidance is provided on the types of ionising radiation that may need to be considered in transport shielding assessments. In general, beta particles (and associated Bremsstrahlung), X rays, primary and secondary gamma rays and spontaneous / alpha-n neutrons need to be considered.

Advice is also given on the analytical and computational methods that can be used to estimate dose rates due to these types of radiation. In simple cases, dose rates may be estimated using published nuclear data and attenuation curves for shielding materials. However, for more complex cases it will usually be necessary to use a computer code.

Appendix 4 Shielding Materials

1. The following guidance is offered to ONR shielding inspectors in considering the shielding materials in designs adopted in safety reviews.
2. Steel is used to provide shielding, containment and structure to reactor systems, including early magnox stations and PWRs. Impurities such as manganese and cobalt should be minimised as they lead to high levels of neutron activation. Steel wool is used as plugging for gaps in, for example, overlapping shielding plates or to fill voids in package internals.
3. Lead is effective as a shielding material because it has a high density and atomic number, is readily workable and is relatively immune from radiation damage. However, it has poor structural properties, particularly above 60°C, and so is often bonded to steel. Antimony is sometimes added to lead to provide hardening, although this increases the neutron activation cross-section. Owing to its high density, construction of lead shields is normally carried out in situ. Therefore there may be potential for significant exposure to workers during the construction phase of projects where the radiation hazard exists (e.g. in decommissioning). Structural support must be adequate to take the weight of such shielding.
4. Lead glass provides effective transparent shielding. It is used in hot cells where there is a need to protect the operator from high radiation fields and also to enable the operator to work with a manipulator. Lead glass shielding is more effective for gamma radiation than neutron radiation, the properties being dependent on the specification of the lead glass.
5. Water is utilised as neutron and gamma shielding, for example, in cooling ponds and is useful for the provision of temporary shielding, particularly in existing dose rate fields (where containers can be filled with water remotely, thus minimising occupancy time during installation). It contains 11% by weight of hydrogen and so is effective in moderating and capturing thermal neutrons. Unlike most of the other shielding materials discussed in this appendix, water is plentiful and cheap.
6. Polythene has a similar density and hydrogen content to water. Its thermal neutron absorption cross-section is sometimes increased by the addition of boron. However, it supports combustion and may distort in even moderate heat, possibly leading to non-uniform shielding. Its use has been effective, for example, in reducing off-site neutron dose rates. It should be noted that with increases in temperature, polythene and materials with similar chemical properties can off-gas leading to the possibility of pressure build up and explosion/fire.
7. Wood in high-density form is also effective as a neutron shielding material. It is easily worked but, like polythene, loss of wood by fire should be considered in the fault analysis.
8. Concrete is relatively cheap, has strong neutron absorption properties (particularly if high hydrogen content) and is a useful structural material. Its gamma attenuation properties can be improved by the addition of steel shot, lead shot, appropriate natural aggregates or the use of special aggregates, e.g. barytes concrete or magnetite concrete.
9. Boral is an aluminium / boron amalgam used to absorb thermal neutrons through the ^{10}B (n, alpha) ^7Li reaction. It is often used as a neutron absorber for criticality control applications.
10. Jabroc consists of laminated beechwood and is also used as a neutron shielding material. Like polythene and wood, jabroc will burn and so loss of shielding in a fire should be considered in the fault analysis.

11. Perspex is often used as a shielding material for beta particles. A depth of 1 cm will stop all beta particles although, for high-energy beta emitters, bremsstrahlung radiation will be emitted.