



ONR GUIDE			
<b>RADIATION SHIELDING</b>			
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## **1. INTRODUCTION**

- 1.1 The Office for Nuclear Regulation (ONR) has established its Safety Assessment Principles (SAPs) which apply to the assessment by ONR specialist inspectors of safety cases for nuclear facilities that may be operated by potential licensees, existing licensees, or other duty-holders. The principles presented in the SAPs are supported by a suite of guides to further assist ONR's inspectors in their technical assessment work in support of making regulatory judgements and decisions. This technical assessment guide is one of these guides.

## **2. PURPOSE AND SCOPE**

- 2.1 This document provides guidance to ONR inspectors in respect of the assessment of nuclear licensees' arrangements for radiation shielding as described in outline in ONR Safety Assessment Principle RP.6 and its associated supporting text in paragraphs 602 – 604, [1]. As with all guidance, inspectors should use their judgement and discretion in the depth and scope to which they employ this guidance.
- 2.2 This guidance is aimed primarily at applications to new facilities. It should also be applied to existing facilities, including modifications and decommissioning activities. For facilities that were designed and constructed to standards that are different from current standards, the issue of whether sufficient measures are available to satisfy As Low As Reasonably Practicable (ALARP) considerations should be judged on a case by case basis.
- 2.3 This guide addresses shielding assessment for nuclear facilities. Guidance for shielding assessment for radioactive material transport packages is given in [2].

## **3. RELATIONSHIP TO LICENCE AND OTHER RELEVANT LEGISLATION**

- 3.1 Of the 36 licence conditions (LC) attached to the standard site licence [3], the following LCs are of particular relevance when assessing the adequacy of radiation shielding provisions.

### **3.2 LC 15: Periodic Review**

The adequacy of the safety case, including shielding aspects, should be reviewed at regular intervals against the current operating conditions, current good practice and statutory requirements to ensure that adequate safety provisions are in place for current and future operations. The periodic review should also consider the potential degradation of shielding materials with time.

### **3.3 LC 19: Construction or Installation of New Plant**

The shielding design of a new facility should be considered at an early stage. Fabrication, construction and installation must be carefully controlled, e.g. to ensure that shielding materials and construction meet the design specification, and doses will be kept ALARP.

### **3.4 LC 20: Modification to Design of Plant Under Construction**

Modifications should be assessed to ensure that they do not impact adversely on the shielding design of the facility (e.g. by changing the shielding material or thickness, requiring increased occupancy or effectively reducing the distance between the source and the wall of a shielded enclosure).

### 3.5 LC 21: Commissioning

Inactive and, where appropriate, active commissioning tests should be carried out to ensure, for example, that design criteria have been met, that streaming through penetrations is adequately controlled and that devices such as interlocked shield doors and gamma-gates are effective. Radioactive sources have been used during commissioning tests in the past. However, there are now techniques that do not use ionising radiation, e.g. ultrasonics, and consideration should be given to the use of these techniques. The ONR assessor may want to seek assurance that the company carrying out the tests has appropriately robust Quality Assurance (QA) procedures in place.

### 3.6 LC 22: Modification or Experiment on Existing Plant

Modifications should be assessed to ensure that they do not impact adversely on the shielding design of the facility (e.g. by changing the shielding material or thickness, requiring increased occupancy or effectively reducing the distance between the source and the wall of a shielded enclosure).

### 3.7 LC 23: Operating Rules

This licence condition requires an adequate safety case to be produced by the licensee. The safety case should include details of all radiation shielding features, e.g. bulk shielding, doors, windows, penetrations, bulges and associated equipment. It should be shown that the annual dose targets will be met and that the annual doses will be restricted to ALARP levels.

### 3.8 LC 24: Operating Instructions

Specific operating instructions for shielding and associated equipment may be required to support any identified limits and conditions identified in the interests of safety as part of operating rules.

### 3.9 LC 25: Operational Records

These include, for example, records of dose rate survey measurements (which provide assurance that the shielding is adequate) and the quality control of materials during construction.

### 3.10 LC 27: Safety Mechanisms, Devices and Circuits

The licensee should identify safety mechanisms, devices and circuits that are important to safety, e.g. shield door mechanisms and interlocks, and ensure that they are adequately maintained in accordance with LC 28.

### 3.11 LC 28: Examination, Inspection, Maintenance and Testing

It is expected that equipment associated with shielding, including shield door mechanisms, interlocks, transfer ports, remote handling devices, shields for penetrations and gamma gates, would form part of the licensee's site-wide arrangements under this licence condition.

### 3.12 The following regulations outlined in the Ionising Radiations Regulations 2017 (IRR17) and Approved Code of Practice (ACoP) [4] are considered relevant to the assessment of radiation shielding provisions.

### 3.13 IRR17 Regulation 8: Radiation Risk Assessments

The licensee must carry out a prior risk assessment in order to identify the measures required to restrict the exposures of workers and the public to ionising radiation. Such measures could include the provision of shielding.

### 3.14 IRR17 Regulation 9: Restriction of Exposure

The restriction of exposure to ionising radiation should, wherever reasonably practicable, be achieved by engineering controls and design features, which could include shielding for normal operations and also for accidents.

### 3.15 IRR17 Regulation 12: Dose Limitation

The annual exposures to ionising radiation of workers and the public should not exceed the limits specified in schedule 3. The provision of shielding is one measure that can be used to restrict exposures to acceptable levels.

## 4. RELATIONSHIP TO SAPS, WENRA REFERENCE LEVELS AND IAEA SAFETY STANDARDS ADDRESSED

SAPs Addressed

4.1 It should be noted that the SAPs [1] form a complete document and should be taken as a whole. It is not appropriate to base an assessment on a few selected principles, possibly taken out of context, without considering all other relevant principles. Indeed, many of the principles are relevant to radiation shielding and the ONR assessor should constantly bear this in mind. Hence, in order to carry out a comprehensive assessment, it will generally be necessary to refer to several other Technical Assessment Guides (TAGs) in addition to this one. This section reproduces the SAP and its associated supporting text that refers explicitly to radiation shielding.

### 4.2 SAPs Principle RP.6

Where shielding has been identified as a means of restricting dose, it should be effective under all normal operation and fault conditions where it provides this safety function.

### 4.3 SAPs Paragraph 602

In particular, the safety case should take into account:

- a) the possible faults that may arise and changes of radiation types and levels during the lifetime of the facility, including any post-operational period prior to final decommissioning;
- b) the incidence of localised levels of radiation due to streaming (e.g. through locations where the shielding is less effective);
- c) the potential for unplanned or uncontrolled movement or loss of shielding (particularly when the shielding is provided by a liquid medium, e.g. in spent fuel ponds (see also paragraph 604));
- d) the installation behind shielding of equipment or components involving regular handling or to which regular access is needed;

- e) worker extremity exposures during handling and manipulation of radioactive sources;
- f) worker exposure to the lens of the eye; and
- g) the potential for unplanned or uncontrolled removal from behind shielding of any source.

#### 4.4 SAPs Paragraph 603

Shielding should be used as an integral part of a wider dose optimisation strategy (for example, considering time of exposure and distance from direct radiation sources) designed to keep exposures ALARP. Where temporary shielding is erected, the predicted dose saved by its use must exceed the dose predicted to be received during its installation and removal.

#### 4.5 SAPs Paragraph 604

Special care should be taken where liquid is used as a shielding material. In such instances, the design should include means to prevent unintentional loss of the liquid, detect such losses and initiate an alarm. A recovery plan for loss of the liquid shielding events should be prepared and rehearsed.

#### Discussion of SAPs

##### SAPs Principle RP.6

- 4.6 This principle stresses that the shielding should be effective under all conditions. Hence, in addition to normal conditions, all reasonably foreseeable fault conditions should be considered. This may include source terms that are higher than expected (out of specification material) and the presence of additional sources (over batching). In many cases the shielding may be required to perform its function during and after a seismic event. Hence, seismic qualification may be required.

##### SAPs Paragraph 602

- 4.7 The nature of the source term may change during the lifetime of the facility. This may be due to changes in the nature of the operations in the facility, i.e. new source materials are introduced, or radioactive decay effects in the source material itself. For example, it is well known that the gamma-ray source strength of a  $^{241}\text{Pu}$  source will increase with time up to around 70 years after manufacture due to the in-growth of  $^{241}\text{Am}$ , which is an intense source of low-energy (60 keV) gamma-rays. Licensees should take such effects into account.

Penetrations in shielding for services and plant items, e.g. manipulators and ventilation ducts, can introduce weaknesses and hence give rise to localised increases in radiation levels. These weaknesses can be a problem in that they could give rise to increased doses to workers without being detected by standard dosimetry techniques, e.g. film badges or Thermo Luminescent Dosimeters (TLDs). Penetrations should be carefully assessed by licensees to demonstrate that any localised increases in radiation levels will not result in excessive doses. Licensees will often provide additional local shielding to ensure that the dose rates through penetrations are acceptable. In many cases it is possible to locate penetrations above head height, thereby helping to minimise increased exposure of the workers.

- 4.8 Some items of shielding are required to be movable, e.g. shield doors between active cells and maintenance areas. The shield door is provided to protect workers in the maintenance area when sources are present in the active cell. In such cases, the licensee must demonstrate that the shield door will provide adequate protection during normal operations and also that there are robust safety measures, e.g. hardwired interlocks, in place to ensure that the shield door cannot be opened when there are sources in the active cell and workers in the maintenance area.
- 4.9 The total radiological risk must be ALARP. This includes the doses to the extremities, the skin and the lens of the eye, as well as whole-body doses. This is clear from IRR17 Regulation 9(1), [4], which states:

*Every employer must, in relation to any work with ionising radiation that it undertakes, take all necessary steps to restrict so far as is reasonably practicable the extent to which its employees and other persons are exposed to ionising radiation.*

Note that there is no differentiation between different parts of the body and so the ALARP principle applies to all doses.

- 4.10 In general, the dose received from a radioactive source depends on time, distance and shielding. ONR assessors should consider whether the licensee has optimised the exposures in terms of these three parameters. For example, the use of installed features can reduce the time required to install temporary shielding. The dose assessment should allow the licensee to identify areas where additional shielding or reduced occupancy times may be beneficial.
- 4.11 Extremity doses will usually arise during the manual handling and manipulation of radioactive sources. In general, wherever reasonably practicable, remote control operations should be chosen in preference to manual handling. In cases where remote control is not reasonably practicable, licensees should consider the use of tongs or other similar handling aids for use with such sources. In addition, as a general principle, the numbers and strengths of all radioactive sources used should be as low as reasonably practicable, consistent with the process requirements.
- 4.12 The annual dose limit for the lens of the eye was reduced when IRR17 was issued in 2017. ONR therefore expect licensees to identify those activities where significant eye doses could be received, to provide suitable dosimetry and to identify any additional protection that is necessary, e.g. goggles to provide beta shielding.
- 4.13 Adequate shielding must be provided for all sources at all times. This means that sources requiring shielding must not be exposed. One way that this is achieved during flask loading/unloading operations is through the use of gamma gates on posting ports. The gamma gate connects to the flask door and has mechanical interlocks to ensure that the gamma gate and the flask door cannot be opened until the flask is correctly in place.

#### SAPs Paragraph 603

- 4.14 Situations may occur, e.g. during decommissioning work, where operations are to be carried out in high dose rate areas and consideration is given to the installation of local shielding. In such cases, the use of portable local shielding, which can be quickly and easily installed, can result in substantial dose savings.
- 4.15 Alternatively, a detailed analysis may show that the dose accrued during installation and removal of the local shielding is actually greater than the dose it would save during the operations. In such cases the ALARP solution may be not to install the shielding.

- 4.16 However, it should be noted that there may be occasions where foreseeable fault sequences give rise to individual doses that could be mitigated by the introduction of temporary shielding.

#### SAPs Paragraph 604

- 4.17 Liquid is used as a shielding material for a number of applications including:
- a) spent fuel immersed in water cooling ponds;
  - b) for temporary shielding purposes; and
  - c) in shielded windows as part of permanently shielded hot cells.
- 4.18 In cooling ponds, the licensee should ensure that adequate shielding is provided for the sources at all times, particularly during source movements where the sources will be lifted off the bottom of the pond, thereby reducing the depth of water shielding.
- 4.19 Interlocks should be provided to prevent the over-raising of sources in cooling ponds. In addition, gamma alarms should be provided to give a means of detection of an abnormal situation. Arrangements should also be in place to replenish the water shielding in the event of a leak.
- 4.20 It should be noted that the optical performance of shielding windows can deteriorate over time due to radiation damage. Moreover, the vulnerability of liquid windows will need to be properly considered as part of the fault analysis, i.e. the possible fault sequence of loss of shielding due to leakage needs to be considered.
- 4.21 Liquid windows, e.g. zinc bromide, are found in several old facilities but ONR would expect new facilities to use lead glass windows. The use of lead glass eliminates the fault sequence of loss of shielding due to leakage.

#### WENRA Reference Levels and IAEA Safety Standards

- 4.22 Part of the specification for the update of the SAPs was to consider the Reactor, Decommissioning and Storage Safety Reference Levels published by the Western European Nuclear Regulators' Association (WENRA), and International Atomic Energy Agency (IAEA) Standards, Guidance and Documents. The update of this TAG also considers the WENRA and IAEA publications for specific applicability.
- 4.23 There are no WENRA reference levels referring explicitly to radiation shielding.
- 4.24 Radiation shielding is mentioned in many IAEA publications, e.g. [5], as a means of restricting exposures to the workforce and the public.

## 5. **ADVICE TO INSPECTORS**

### Source Term Generation

- 5.1 As a general principle, the number of radioactive sources used and the strengths of all the sources should be as low as reasonably practicable, consistent with the process requirements. The three factors time, distance and shielding should then be optimised to reduce doses to ALARP levels.

- 5.2 In considering the validity of shielding calculations, ONR assessors should seek assurance that the source terms used are adequately 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. This is a complex area and the source terms should be fully justified by the licensee.
- 5.3 The types of radiation that need to be considered include: alpha particles, beta particles, primary and secondary gamma-rays (including bremsstrahlung), X-rays and primary and secondary neutrons (including photoneutrons). Note that bremsstrahlung may need to be considered where high energy beta sources and high atomic number absorbers are present.
- 5.4 Alpha sources do not generally present an external radiation hazard since the outer dead layer of the skin stops most alpha particles. High-energy beta particles can present an external radiation hazard but are relatively easily shielded. In contrast, gamma-rays, X-rays and neutrons are more penetrating and may require significant thicknesses of shielding material. ONR assessors should seek assurance that all significant sources of penetrating radiation have been identified and quantified.
- 5.5 The three most common sources of gamma-rays are: 1) decay of excited states in daughter nuclei populated by alpha and beta decay, 2) fission and 3) (n, $\gamma$ ) reactions. The most common sources of neutrons are: 1) spontaneous fission, 2) induced fission and 3) ( $\alpha$ ,n) reactions, particularly involving low atomic number nuclei.
- 5.6 In considering source terms used in the calculations, licensees should consider radiation emissions, decay chains, energies, branching ratios and the potential for sub-critical neutron multiplication and criticality incidents. Specific activities should be adequately characterised by reference to standard texts. The physical distribution of the source should be taken into account, including the possible effects of self-shielding.
- 5.7 In shielding problems, consideration should be given to secondary radiations, e.g. secondary gamma-rays, photoneutrons, produced in the shielding materials. Secondary radiations can require significant amounts of shielding since they often have relatively high energies and are not attenuated by the full thickness of the shielding material since they may be produced within the shielding material.
- 5.8 Consideration should also be given to the neutron activation of materials. Such activated impurities can be significant sources of gamma-rays. For example, structural steel work is used in nuclear facilities and  $^{59}\text{Co}$  impurities in steel can be activated to  $^{60}\text{Co}$  by neutron capture, which emits relatively high-energy gamma-rays. The potential for neutron activation should be minimised through the appropriate choice of materials (e.g. high-purity steels) or reducing the neutron flux to items that may become activated (e.g. providing neutron shielding or relocating equipment).
- 5.9 A similar neutron activation effect can occur in lead. Antimony is sometimes added to lead to improve its structural strength. However, the antimony can be activated by neutrons. Another example of neutron activation occurs in nuclear reactors. Here, (n,p) reactions on  $^{16}\text{O}$  in the coolant (carbon dioxide in AGR, and water in PWR) produce radioactive  $^{16}\text{N}$ . Although the cross-section for this reaction is small, the massive neutron flux in a reactor core leads to the production of significant quantities of  $^{16}\text{N}$ . This isotope has a short half-life and decays away within a few seconds once the reactor is shut down. However, it is a source of high-energy (6 and 7 MeV) gamma-rays and can hence present a problem when the reactor is operating.
- 5.10 Licensees should address the possible deposition of radioactive material onto the inner surfaces of vessels and pipework in plants handling active liquors. This effect is known

as plate-out. Although the bulk liquor will dominate dose rates through the bulk shielding during normal operations, the plated-out material will be the dominant source during maintenance and decommissioning operations when the vessels and pipes are drained and the bulk shielding is removed. In cases where plate-out is significant, decontamination facilities and local shielding may be required to restrict doses to acceptable levels. Licensees should be aware that source terms may increase due to unforeseen accumulations in unexpected locations.

- 5.11 Consideration should be given to the significance of bremsstrahlung in cases where intense beta sources are present. Note that the significance of bremsstrahlung increases as the energy of the beta particles and the atomic number of the shielding material increase. Low atomic number elements are often chosen as shielding materials for beta particles in order to minimise the production of bremsstrahlung.
- 5.12 It may be necessary to provide secondary shielding (e.g. steel or lead) to absorb any bremsstrahlung produced by beta particle interaction with high atomic number materials. The sequencing of primary and secondary shielding materials may be important in terms of providing effective shielding, e.g. for neutron sources, some metal shielding may be required after, i.e. on the cold side of, the neutron shielding to absorb secondary gamma-rays. The use of secondary shielding may introduce additional hazards that need to be addressed, e.g. construction hazards and fire hazards.
- 5.13 Consideration should be given to the possibility of introducing more intense sources during the lifetime of the facility and of the need to anticipate the requirement for additional shielding. In particular, providing additional shielding during the design stage does not result in additional dose accrual, whereas back-fitting additional shielding once a plant is operational will invariably incur some level of dose accrual.

#### Hierarchy of Protection

- 5.14 The number and strengths of the radioactive sources should be reduced as far as reasonably practicable. Safety measures should then be provided to restrict doses to ALARP levels.
- 5.15 The need to follow the hierarchy of protection is addressed in Regulation 8(2) in IRR17, [4]. This is echoed in principle RP.7 in the SAPs, [1]. Engineered safety features include shielding, ventilation, containment, remote handling and interlocks. Operational safety features, which may reduce exposure to the hazard during planned operations, include management control arrangements including restrictions on occupancy, monitoring arrangements and alarms, pre-planning of exposure and the use of barriers and notices.
- 5.16 The widely accepted hierarchy of protection specifies the following order of preference for safety measures:
- i. Passive engineered safety measures.
  - ii. Active engineered safety measures.
  - iii. Administrative safety measures.
- 5.17 Hence, passive engineered safety measures, e.g. shielding, should be preferred to active engineered safety measures and administrative safety features.
- 5.18 Where there is reliance on operational safety measures, there may well be a need for operating rules to be specified. Means of preventing unplanned or uncontrolled

removal of sources from behind shielding include door interlocks, gamma gates, dose rate meters and alarm systems to initiate a warning if a source is exposed.

- 5.19 Management controls should ensure that operators are aware of the safety significance of shielding and that it is not dismantled without the necessary authority. This control can be exercised through local rules, work permits and training. A similar level of control is required when the shielding is reassembled.

#### ALARP

- 5.20 Shielding is an important means of restricting exposure to ionising radiation and ensuring that doses are ALARP. Guidance on the demonstration of ALARP is given in [6].
- 5.21 ONR expect licensees' safety cases to include a demonstration that annual doses received by workers and members of the public will be controlled at levels which are As Low As Reasonably Practicable (ALARP) under all conditions. This may be achieved, in part, by the design and provision of adequate shielding.
- 5.22 Shielding is usually designed to achieve targets for dose rates at the external surface of the shielding. However, doses to operators are controlled, not only by providing shielding, but also by optimising the period of exposure and distance from the source. ONR assessors should note the three basic methods of control of external exposure: time, distance and shielding. Therefore, shielding design should not be considered in isolation but as part of a wider optimised ALARP strategy.
- 5.23 Licensees may seek to justify limited quantities of bulk shielding (or none at all) on the basis of Cost Benefit Analysis (CBA). ONR assessors should consider such arguments as part of the licensee's wider ALARP case, bearing in mind that, in good radiological protection practice, priority should be given to controlling the source of ionising radiation by passive design features and engineering safety systems, rather than by placing controls on individuals or by reliance on management controls.
- 5.24 It should be noted that CBA is only one possible input into the overall ALARP decision-making process. In particular, the results of a CBA are always subject to uncertainty and so the conclusions should be viewed with caution. Primary consideration should be given to relevant good practice, which may override the conclusions of a CBA.

#### Calculation Methods

- 5.25 Licensees use a variety of hand calculation methods, [7] to [15], and computer codes in designing and assessing shielding. ONR assessors should consider the suitability and adequacy of these as appropriate.
- 5.26 ONR assessors may wish to consider whether computer calculations using statistical methods, e.g. point kernel and Monte Carlo, are adequately sampled and converged.
- 5.27 Calculations should include an analysis of uncertainties, systematic bias (e.g. from factors such as changes in structural materials), modelling approximations and uncertainties in nuclear data. The licensee should put appropriate peer review arrangements in place to provide confidence in the results of shielding calculations. In some cases, ONR assessors may use standard hand calculation methods and shielding data to carry out simple scoping calculations to check the licensee's safety case. They may also choose to let a contract for sample calculations to be checked by suitable consultants using an appropriate computer code.

- 5.28 It is important that the geometries used in calculation codes are sufficiently detailed to ensure all significant radiation paths are included. This may require the model to include walls, floors, ceilings and large items of equipment which radiation scatter off to impact operator positions; this is particularly important for neutron radiation problems where scatter paths can be a significant contributor to doses. Conversely, it may also be appropriate for calculations to omit items from the geometry that have little impact on the results (e.g. bolts on a flask or the support frame for a glove box). ONR assessors should also be aware of the methods used to model geometries in calculation codes such as user defined (input by the shielding assessor) or Computer Aided Design (CAD) import (imported from 3D design software) as both methods have the potential to introduce errors and uncertainties in results.
- 5.29 Users of computer codes should be aware of current advice from the code suppliers, particularly regarding potential code errors. Such errors are more likely when dealing with complex or novel shielding applications where there may be limited experience of using a specific code and where validation data may not be readily available. In some cases these errors may be significant. Calculations using an additional method can, however, provide some reassurance in such cases.
- 5.30 Penetrations through bulk shielding can be difficult to assess. Care is required when carrying out computer calculations to assess penetrations to ensure that the weak paths have been adequately sampled. Hand calculations may offer a suitable alternative to computational methods where only gamma radiation needs to be considered. However, penetration calculations where neutron radiation is significant almost always require computational methods.
- 5.31 The licensee should be able to provide evidence that it has constructed a comprehensive schedule of all penetrations through the bulk shielding and has conducted a documented shielding assessment of each penetration recorded within the schedule (either via individual assessments or by grouping penetrations and assessing a single 'worst-case' penetration that covers all the other penetrations within that grouping). NB Documented plant walk-downs, to ensure the penetrations schedule is comprehensive, are considered to be relevant good practice.
- 5.32 It is important that any hand calculation method or computer code used by a licensee should be demonstrated to have appropriate verification and validation in order to provide adequate confidence in the results.
- 5.33 Validation should be demonstrated by reference to benchmark experiments wherever possible. In cases where experimental data are not available, validation by comparison with an independent method may be acceptable. Further guidance on validation is given in [16].
- 5.34 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.
- 5.35 ONR would expect that shielding analysts and peer reviewers in the licensee's organisation are suitably qualified and experienced. Evidence may be sought of academic qualifications, professional training and continual professional development.
- 5.36 ONR assessors may seek assurance that licensees have used appropriate parameters, such as flux to dose rate conversion factors and radiation and tissue weighting factors as recommended by the International Commission on Radiological Protection (ICRP).

### Solid Shielding Materials

- 5.37 Shielding designs vary according to the nature of the ionising radiation presenting the hazard. In terms of solid shielding materials, concrete, steel and lead are frequently used for gamma rays, and polythene, borated plastics, concrete and wood for neutrons. Guidance on shielding materials is given in Appendix 1.
- 5.38 It should be noted that the introduction of shielding materials can introduce additional hazards. Therefore, the shielding design and the safety case should take account of the capability of materials to withstand the effects of foreseeable fault conditions. For example, high temperatures from a fire could cause lead shielding to melt or hydrogenous neutron shielding materials to burn. It should be noted that variants of certain shielding materials exist, which have enhanced fire-retardant properties. Failure of the shielding material in certain faults could lead to very high radiation fields. It is therefore important to ensure that the shielding materials are fit for purpose.
- 5.39 Consideration should be given to neutron streaming through steel where water or polythene is used as the primary neutron shielding material with localised regions consisting of steel.
- 5.40 Radiography equipment often uses very intense sources of radiation, with the potential to result in very large doses (of the order of several Grays) during accidents. Hence, significant bulk shielding is required for radiography enclosures. In addition, interlocked doors are required to prevent access to the radiation area when the source is exposed or energised. Further guidance on shielding considerations in enclosure radiography and also for site radiography is provided in [17].
- 5.41 ONR assessors may seek assurance from licensees that there are no degradation mechanisms, e.g. radiation damage or change of shape due to heating that will compromise the effectiveness of solid shielding materials as the facility ages.

### Liquid Shielding Materials

- 5.42 Water is used as a shielding material in fuel storage ponds since it is cheap, transparent, allows fuel movements to take place without loss of shielding, and facilitates cooling of the fuel. In addition, zinc bromide solution has been used in the past for windows in hot cells.
- 5.43 In Pressurised Water Reactor (PWR) plants, advantage has been taken of the shielding effect provided by the water in the primary circuit to achieve dose reductions during maintenance activities. In particular, the water is left in the primary circuit until certain potentially dose-intensive maintenance activities have been carried out.
- 5.44 In cases where liquid shielding is used, the ONR assessor may wish to confirm that there is no reasonably foreseeable mechanism where the liquid could leak away. The use of liquid shielding in windows, e.g. zinc bromide solution, in new plants should be discouraged since solid shielding in the form of lead glass is now available. However, the assessor should consider the impact of the use of lead glass on neutron dose rates, since lead glass represents a poor neutron shield.
- 5.45 As with solid shielding materials, ONR assessors may seek assurance from licensees that there are no degradation mechanisms, e.g. radiolysis or change of shape due to heating that will compromise the effectiveness of liquid shielding materials as the facility ages.

### Novel Shielding Materials

- 5.46 Most of the common shield materials have been in use for many years and their properties are well understood. However, a licensee may occasionally propose a novel shielding material, e.g. one which is relatively light and has particularly good structural strength.
- 5.47 In such cases, ONR assessors may seek assurance from the licensee that the shielding properties of the material are adequately characterised, it will be constructed in accordance with its specification and that it will continue to provide effective shielding throughout the facility lifetime, i.e. that there are no degradation mechanisms that will compromise the effectiveness of the shielding as the facility ages.

### Temporary Shielding

- 5.48 Situations may arise where temporary shielding is used instead of permanent shielding. For example, it may not be reasonably practicable to install permanent bulk shielding during site radiography. In these cases, temporary shielding may be required in order to restrict doses to acceptable levels. Such occasions should be covered by an adequate safety justification.
- 5.49 Temporary shielding has been used to good effect by some licensees to reduce dose rates from contaminated vessels and pipework during maintenance operations.
- 5.50 Consideration should be given to the method used to install and remove the shielding to ensure that the doses to the workers carrying out these tasks are optimised in terms of time, distance and shielding.
- 5.51 The use of installed features can reduce the time required to install temporary shielding. In addition, the dose assessment should allow the licensee to identify areas where additional shielding or reduced occupancy times may be beneficial.
- 5.52 In cases where temporary shielding is provided, structural analysis may be required to demonstrate that the structure supporting the shielding can withstand the additional load.
- 5.53 Water can also be used to provide temporary local shielding for special planned operations in relatively high dose rate areas. For example water-filled containers, which are cheap and can usually be installed relatively quickly, thereby optimising the time of exposure, may be suitable for bulk shielding.

### Dose and Dose Rate Targets

- 5.54 Numerical target 1 in the SAPs specifies a number of numerical targets as well as legal limits for annual doses to the whole body for people working on the licensed site. The legal limits are taken from the IRR17, [4].
- 5.55 As stated in IRR17 Reg 8(1), it is also a legal requirement to restrict exposures to ALARP levels and so, in general, licensees must implement measures to ensure that doses are driven down below the legal limits.
- 5.56 Although not specified in the SAPs, licensees will often specify dose rate targets for shielding design purposes. For bulk shielding in highly occupied areas, dose rates no higher than 0.5 microSv/h in highly occupied areas are unlikely to attract much regulatory attention. (This corresponds to an annual dose of 1 mSv for 2000 hours occupancy.)

- 5.57 It may be appropriate to allow higher dose rates in areas with restricted occupancy, e.g. in normally locked cells, where access is only required on an infrequent basis for maintenance or inspection purposes. However, licensees should still demonstrate that the doses received in such areas will be ALARP.
- 5.58 It may also be appropriate to allow moderately higher dose rates in occupied areas provided that the radiation field is transient and localised, such that significant radiation exposure cannot occur. Again, the doses received must be shown to be ALARP.
- 5.59 Where appropriate, the licensee should undertake a suitably detailed dose assessment which provides estimated task durations, dose rates and doses associated with specific tasks and activities. This should enable the licensee to identify the higher dose tasks which should be the focus of dose reduction measures (e.g. reducing task times, increasing distance from source and the provision of additional shielding). The dose assessment should help form the basis for demonstrating compliance with dose criteria and support the justification for doses being ALARP.

#### Commissioning

- 5.60 The adequacy of the shielding should be tested during commissioning activities to confirm that the design intent will be met. These tests may be based on installed or portable instrumentation.
- 5.61 Weaknesses in the shielding should be identified during commissioning of a new facility and by regular radiation surveys carried out by the licensee. ONR assessors should consider the adequacy of any remedial treatment, i.e. engineered solutions incorporating additional local shielding are to be preferred over operational access restrictions.
- 5.62 Radiation surveys may not pick up increases in radiation levels. Hence, there is a need for periodic review of worker dose records. Details of ONR's expectations for periodic reviews of safety are presented in [18].

#### Normal Operations and Fault Scenarios

- 5.63 Although shielding is designed mainly to reduce exposures to radiation during normal operations, the licensee should also consider the extent of installed shielding that would be reasonably practicable to mitigate workforce and public exposures in the event of accidents e.g. out of specification source material or over batching of sources.
- 5.64 A criticality accident can give rise to very high doses and dose rates. In cases where fissile materials are being handled, it may be reasonably practicable to provide additional shielding at the design stage to reduce doses in the event of a criticality accident. Consideration should also be given to the recovery activities that may be required following a criticality incident.

## Maintenance

- 5.65 Wherever reasonably practicable, designs should enable maintenance work and handling of components within shielded enclosures to be carried out without breaching the shielding. Devices such as pumps serving equipment in shielded enclosures may be located outside the enclosure but the design should ensure that the design intent of the shielding is not compromised.

Extract filters serving ventilated shielded enclosures are often located outside the enclosure to enable external access. In such cases there may be a need for the filter housing to be provided with additional local shielding. In radiochemical plants, for example, relatively high dose rates can develop as material accumulates on the filter. An alternative solution may be to change the filters more frequently, before enough material has accumulated on the filters to result in unacceptably high dose rates.

- 5.66 The layout of engineered systems should facilitate maintenance and should be designed with the need to restrict exposures to ALARP levels in mind. For example, where devices are required to operate within shielded enclosures, parts requiring maintenance should, if reasonably practicable, be located outside the shielding.

## Decommissioning

- 5.67 ONR assessors may need to consider arguments for decommissioning projects where the design of shielding may be constrained by the structural strength needed to support its weight and by the potential exposure of workers installing the shielding. Remote equipment may obviate the need for additional shielding (except, perhaps, during installation of the equipment).
- 5.68 In addition, source characterisation can be difficult for decommissioning projects for old plants where detailed operational records may not be available. In such cases, ONR assessors may seek assurance that licensees have carried out adequate measurement campaigns to characterise the source material.

## Protection of the Public

- 5.69 For chemical processing facilities and other nuclear facilities, the shielding provided to protect workers normally ensures that the numerical dose target is met for members of the public. However, ONR assessors may pay special attention to operations located close to the site perimeter fence.
- 5.70 Of particular interest may be the contribution from skyshine, or radiation scattered in the air. This mechanism can contribute to significant off-site doses, particularly if the source covers a large area, for example, a large storage area for waste containers.
- 5.71 For power reactor sites, the biological shield of the reactor is fundamental in limiting doses to members of the public off the site. Where the shield is penetrated, for example at the top duct of magnox reactors with steel pressure vessels, there may be discrete beams of neutron radiation. In such cases, the provision of polythene shielding on and near the boiler roof has proved effective in significantly reducing off-site dose rates.

## UK Shielding Forum

- 5.72 ONR assessors should be aware of the work 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. The 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 the Forum.

## Assessment Guidance

- 5.73 This section presents suggested guidance in the form of a series of points the ONR assessor may look for when considering a licensee's shielding assessment. This list is not exhaustive.
- i. Comprehensive and conservative source term derivation.
  - ii. Compliance with the hierarchy of protection, i.e. preference given to passive engineered safety measures such as shielding.
  - iii. Adequate ALARP assessment.
  - iv. Appropriate choice of calculation methods, i.e. computer codes and/or hand calculations.
  - v. Adequate sampling and convergence of computer calculations.
  - vi. Adequate verification and validation of calculation methods.
  - vii. Adequate cross checks of calculations using independent methods.
  - viii. Demonstration that the shielding materials are fit for purpose throughout the lifetime of the facility.
  - ix. Peer review carried out where appropriate.
  - x. Confirmation that the licensee's shielding analyst and peer reviewer are suitably qualified and experienced (SQEP).

## 6. REFERENCES

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## 7. GLOSSARY AND ABBREVIATIONS

AGR	Advanced Gas Cooled Reactor
ALARP	As Low As Reasonably Practicable
CAD	Computer Aided Design
CBA	Cost Benefit Analysis
DBA	Design Basis Analysis
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRR17	Ionising Radiations Regulations 2017
LC	Licence Condition
ONR	Office for Nuclear Regulation
PWR	Pressurised Water Reactor
QA	Quality Assurance
SAPs	Safety Assessment Principles
SQEP	Suitably Qualified and Experienced
TAGs	Technical Assessment Guides
TSF	The Shielding Forum
TLD	Thermo Luminescent Dosemeter
UKNSF	United Kingdom Nuclear Science Forum
WENRA	Western European Nuclear Regulators Association
WPC	Working Party on Criticality

## 8. APPENDIX 1 – SHIELDING MATERIALS

1. The following guidance is offered to ONR assessors in considering the shielding materials in designs adopted in safety cases.
2. Steel is used to provide shielding, containment and structure to reactor systems, including early magnox stations and PWRs. Structural steel work is also used in chemical plants. Impurities such as manganese and cobalt should be minimised as they lead to high levels of neutron activation.
3. Lead is effective as a gamma-ray 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. Lead wool is used as a plugging for gaps in, for example, overlapping steel shielding plates. Care must be taken with the tamping to ensure that the gaps are properly sealed. It is important that the effectiveness of any lead wool plugging is determined by active commissioning tests. Care must be taken when handling lead due to its toxicity,
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.
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. (Note that jabroc is a form of wood, as discussed below).
8. Concrete is relatively cheap, has strong neutron absorption properties and is a useful structural material. Its gamma-ray 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 encased by aluminium plates used to absorb thermal neutrons through the  $^{10}\text{B} (n, \alpha) ^7\text{Li}$  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. For low energy beta emitters (e.g.  $^{35}\text{S}$ ,  $^{14}\text{C}$ ), 3 mm of Perspex will stop all beta particles.
12. Various commercial materials are often used for grouting.
13. Lead acrylic (e.g. Premac) is transparent polycarbonate containing lead (typically 30% lead by mass) and is often employed in plutonium plants (i.e. windows and gloveboxes). This is due to the high hydrogen content providing significant neutron shielding, whereas the lead content provides gamma shielding and is particularly effective at shielding the intense low energy gamma radiations arising from decay of  $^{241}\text{Am}$ .